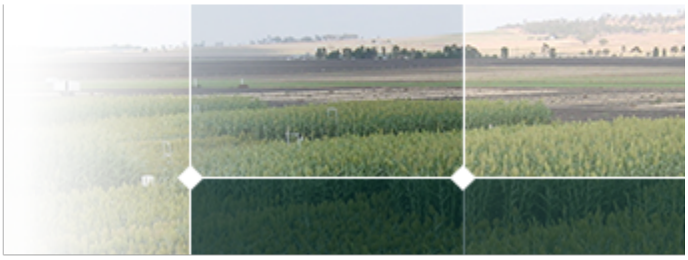


1 The APSIM SoilTemperature Model

Val Snow (AgResearch, New Zealand) and Dean Holzworth (CSIRO, Australia)

Tested against data and simulaitons supplied by:

- Neil Huth (CSIRO, Australia)
- Sotirios Archontoulis and Isaiah Huber (Iowa State University, USA)
- Hamish Brown (Plant and Food Research, New Zealand)

2 Acknowledgements

SoilTemperature was completed using funding from AgResearch’s Strategic Science Investment Fund and CSIRO’s internal funding (SIP).

3 Introduction

SoilTemperature simulates soil temperature given minimal input information using a numerical scheme. This implementation is largely based on the method described by Campbell (1985) but has some modifications to make it compatible with APSIM. There are also some updates since the version released in APSIM Classic. This model replaces the former method that was based on EPIC (Williams xxxx).

4 High-level Description

See Campbell (1985) for details on the numerical scheme - the mathematics is not replicated here. The soil thermal properties that are needed for the numerical solution are the specific heat capacity (the quantity of energy needed to raise the soil temperature by 1 C) and the thermal conductivity (the ability of the soil to conduct heat). These properties are estimated from standard APSIM soil properties using methods from Campbell (1985), Tian et al., (2016) and de Vries (1963) taking into account the possibility that the soil has rocks, ice and high organic matter contents. If the particle size information for the soil is not supplied then they are estimated as 30% clay, 65% silt and 5% sand with these values displayed in red in the user interface so that better values may be supplied if available. Initial values of soil temperature may be supplied by the user and if not they are estimated from a standard simple analytical equation. SoilTemperature runs 48 timesteps within each day. The upper boundary condition during the day is interpolated using a sine function from the minimum and maximum air temperature for the day. The lower boundary condition is set at 20 m deep as the annual average air temperature. To allow this deep lower boundary condition SoilTemperature includes a number of ‘phantom’ layers below the user-specified soil profile. The properties of these layers are set to equal those in the deepest simulated layer and their only purpose is to facilitate the implementation of the lower boundary condition. These nodes are invisible to the user.

5 References

Campbell, G.S., 1985. Soil Physics with BASIC. Transport Models for Soil - Plant Systems. Elsevier, Amsterdam.

de Vries, D.A., 1963. Thermal properties of soils, in: van Wijk, W.R. (Ed.) Physics of Plant Environment. North-Holland Publishing Corporation, Amsterdam, pp. 210–235.

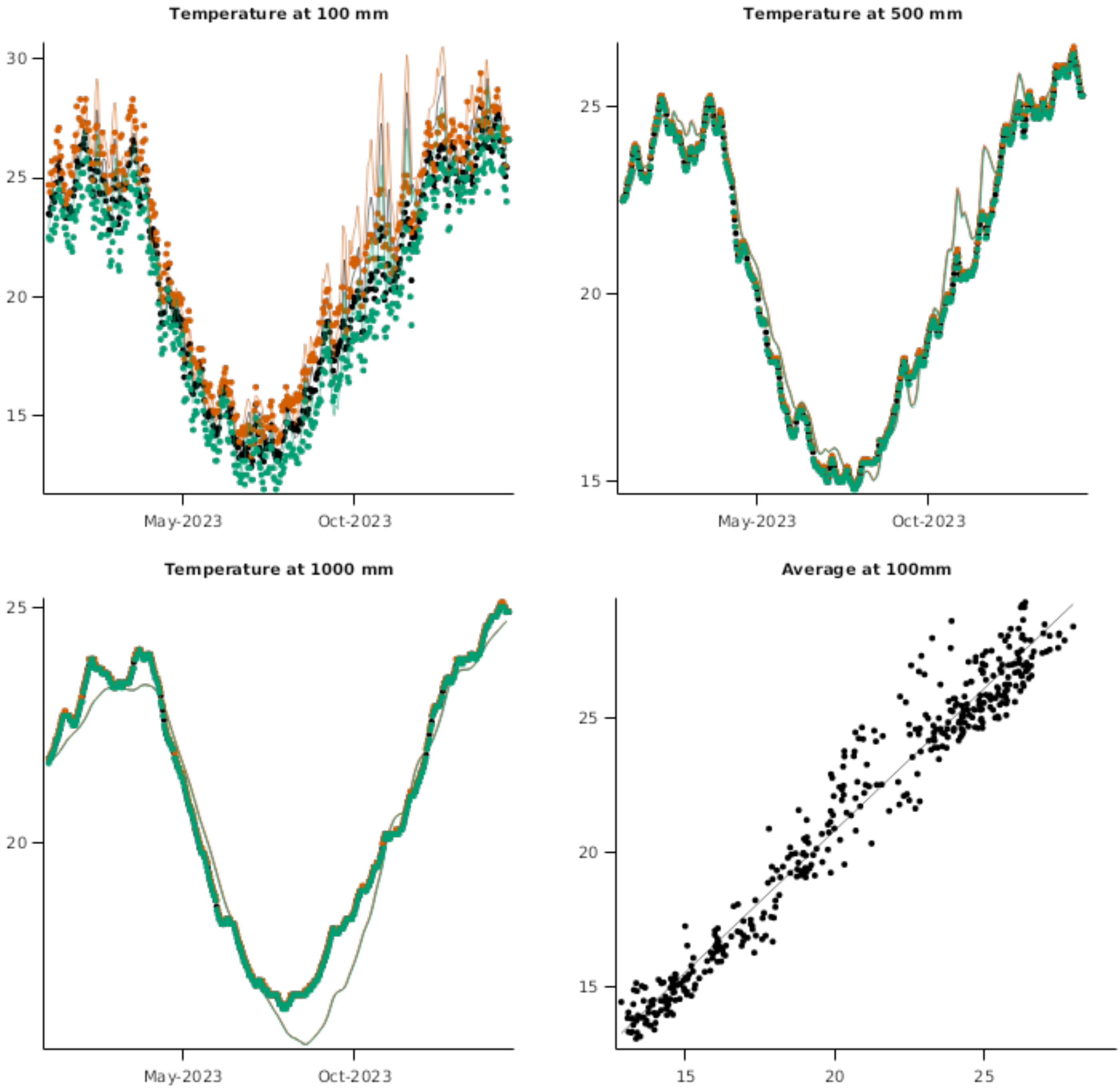
Tian, Z., Lu, Y., Horton, R., Ren, T., 2016. A simplified de Vries based model to estimate thermal conductivity of unfrozen and frozen soil. Eur. J. Soil Science. 67(5), 564-572. https://doi.org/10.1111/ejss.12366.

6 ValidationTests

6.1 ForestHill

6.1.1 ForestHillWeatherStation

ForestHillWeatherStation

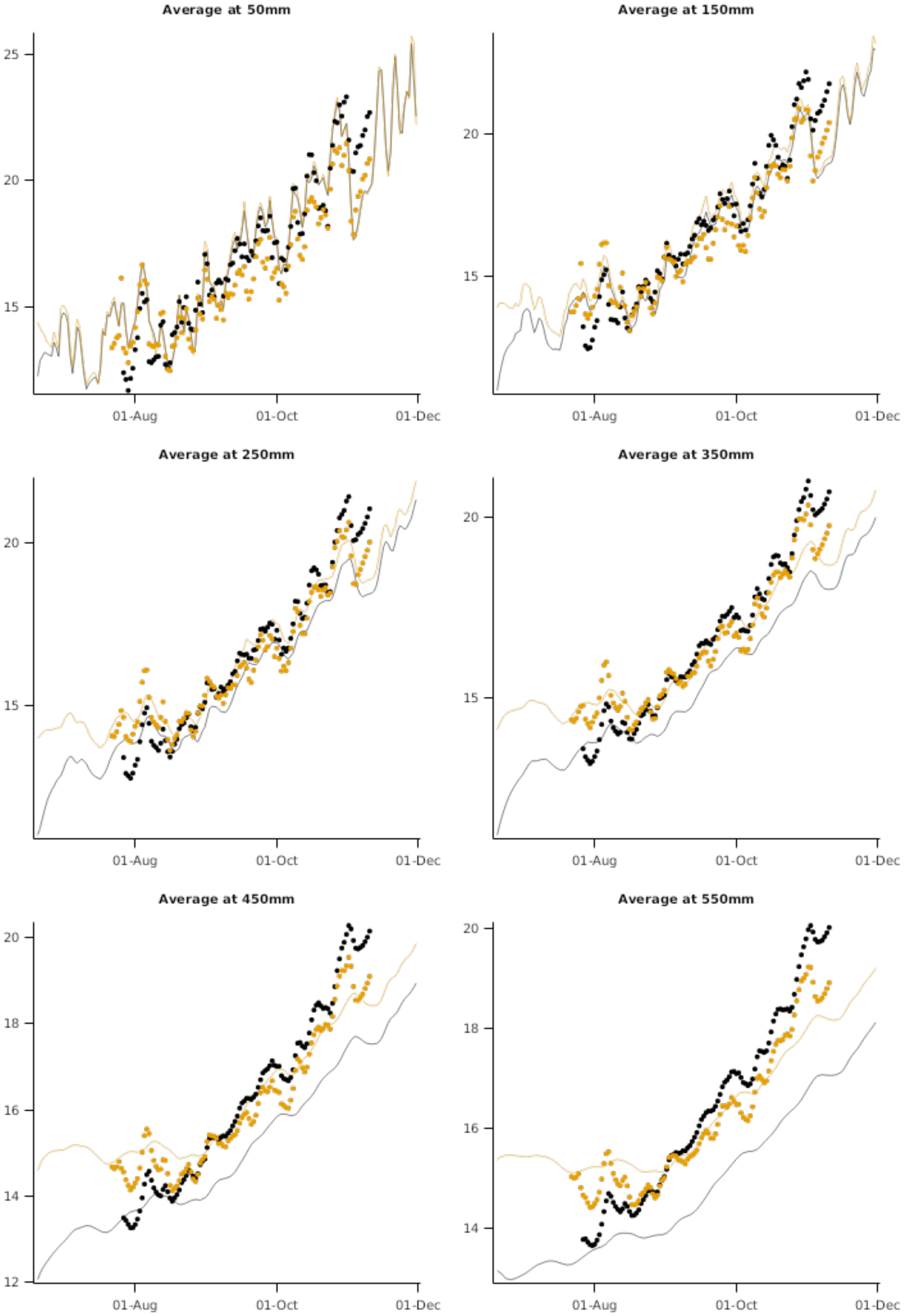


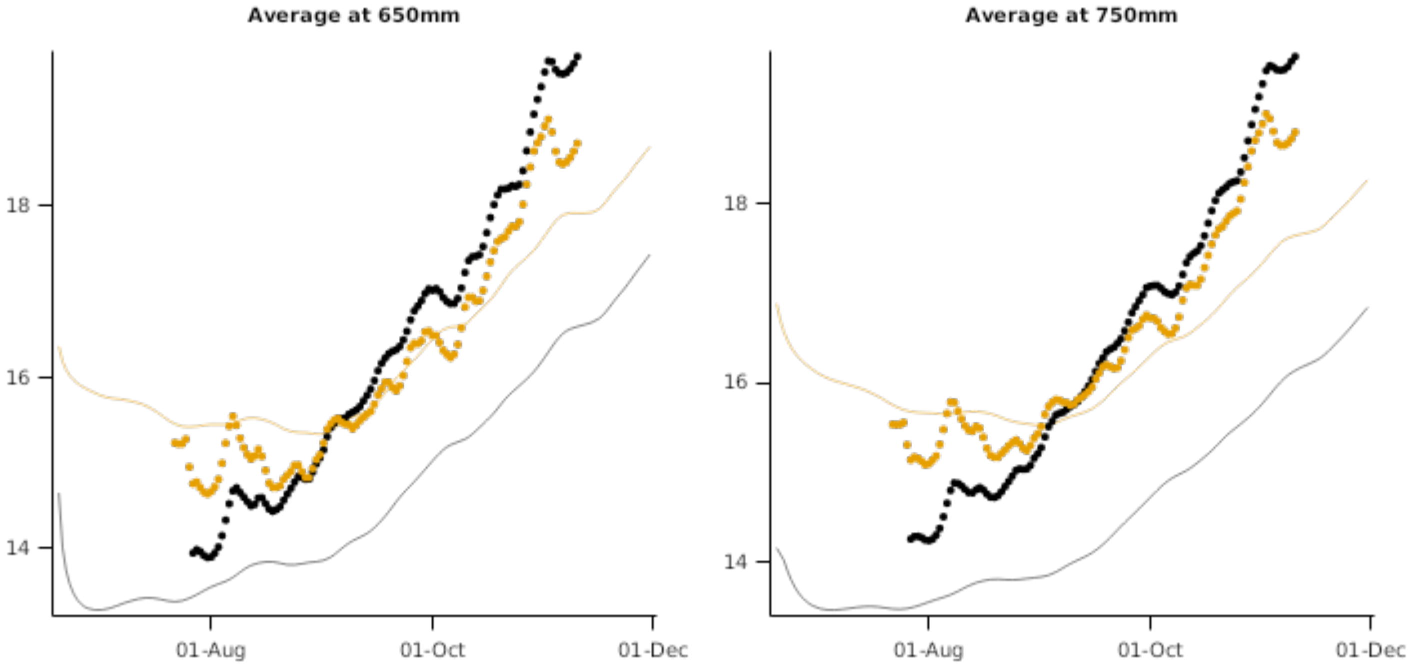
6.1.2 ForestHillWheat

List of experiments.

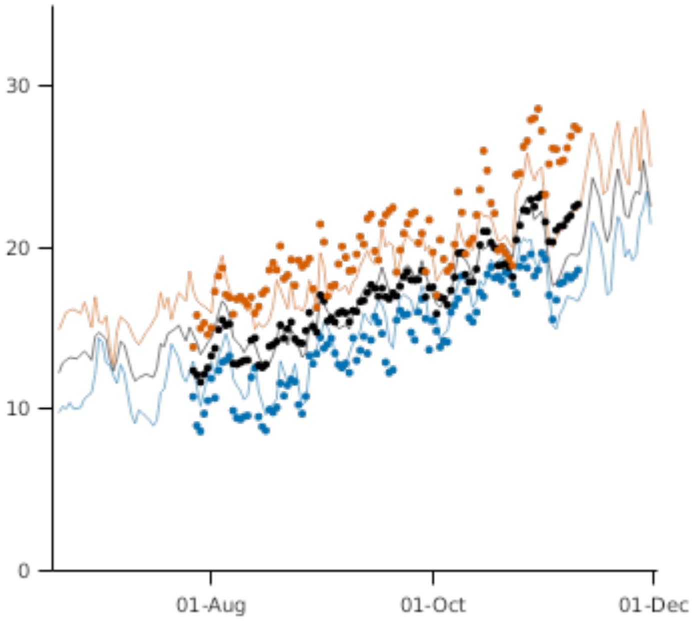
Experiment Name	Design (Number of Treatments)
ForestHillWheat	(2)

6.1.2.1 Comparison of averages soil temperature

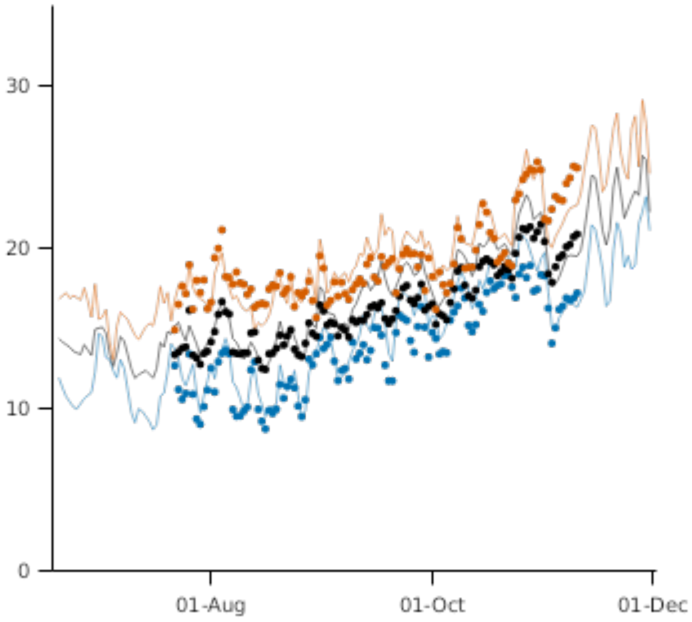

Average at 50mm
25
20
15
01-Aug
01-Oct
01-Dec
Average at 150mm
20
15
01-Aug
01-Oct
01-Dec
Average at 250mm
20
15
01-Aug
01-Oct
01-Dec
Average at 350mm
20
15
01-Aug
01-Oct
01-Dec
Average at 450mm
20
18
16
14
12
01-Aug
01-Oct
01-Dec
Average at 550mm
20
18
16
14
01-Aug
01-Oct
01-Dec



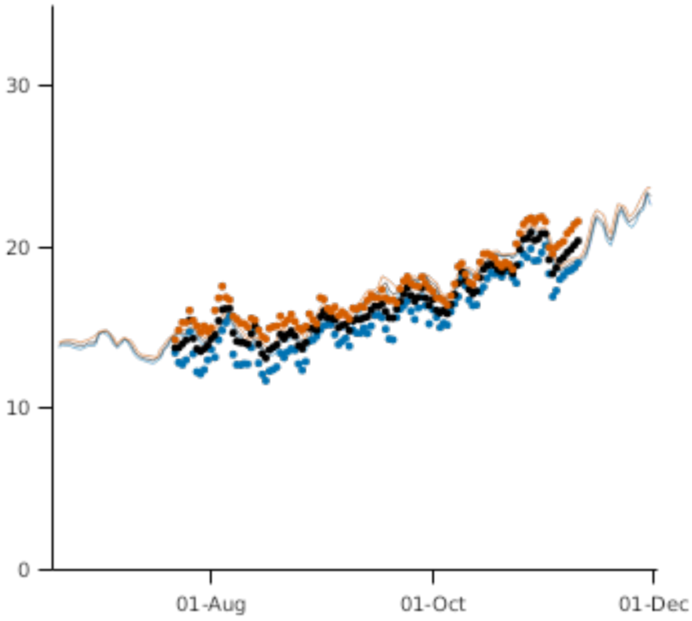
6.1.2.2 Comparison of diurnal ranges



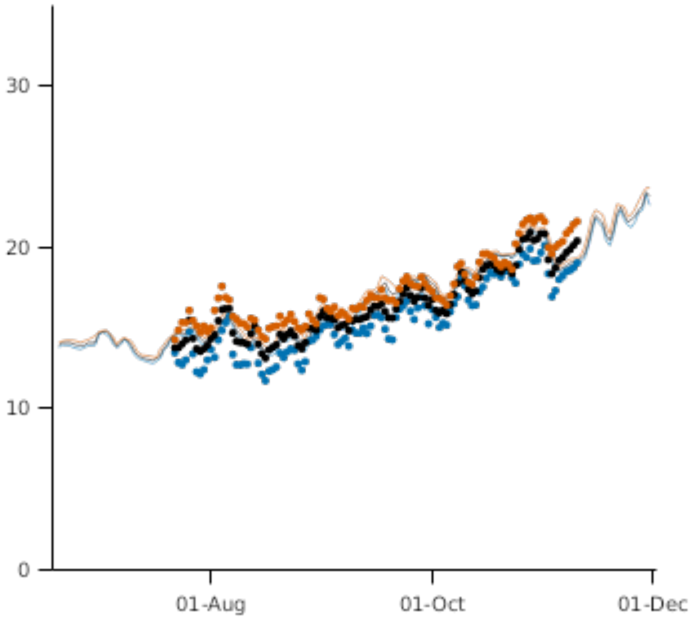
TentHill 50mm



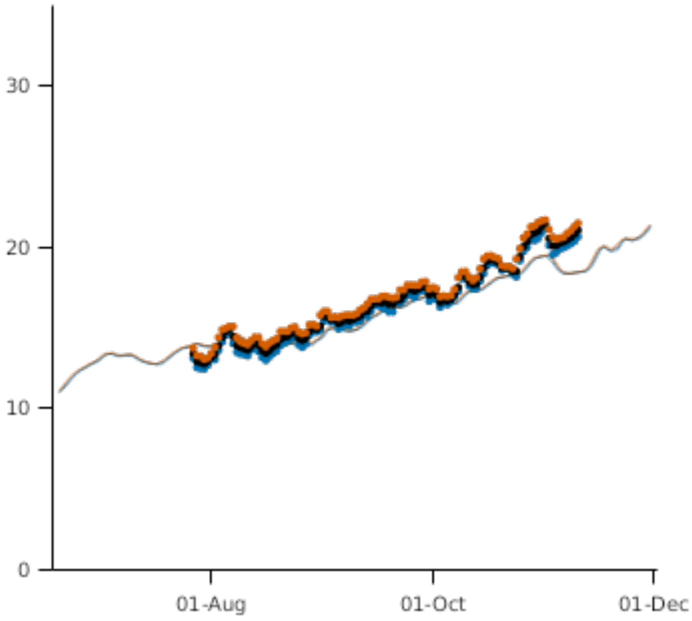
Cavendish 50mm



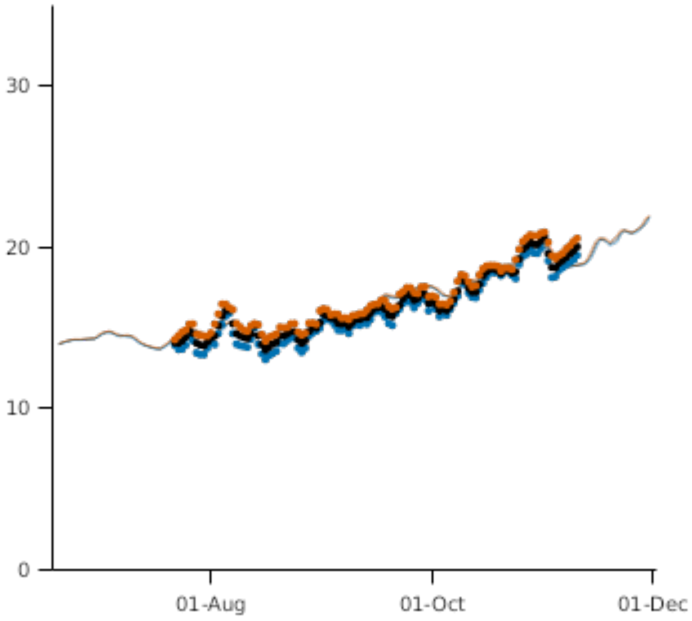
Cavendish 150mm



Cavendish 150mm1



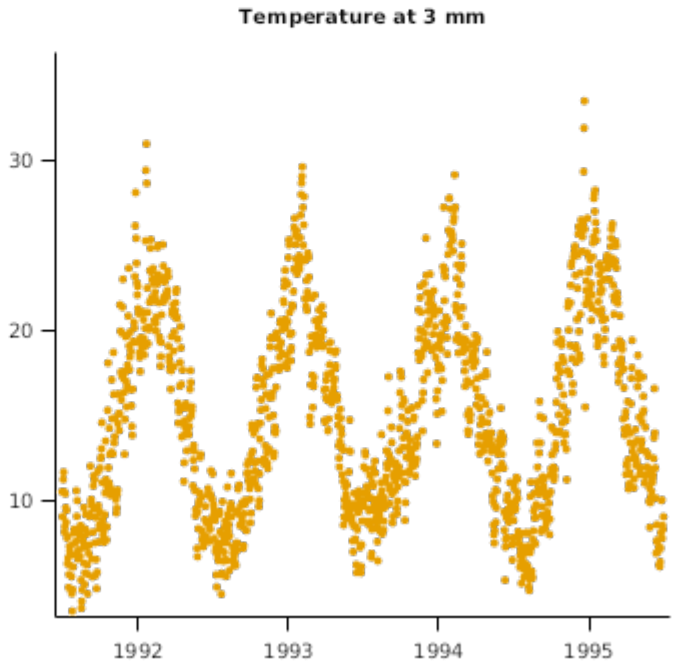
TentHill 250mm

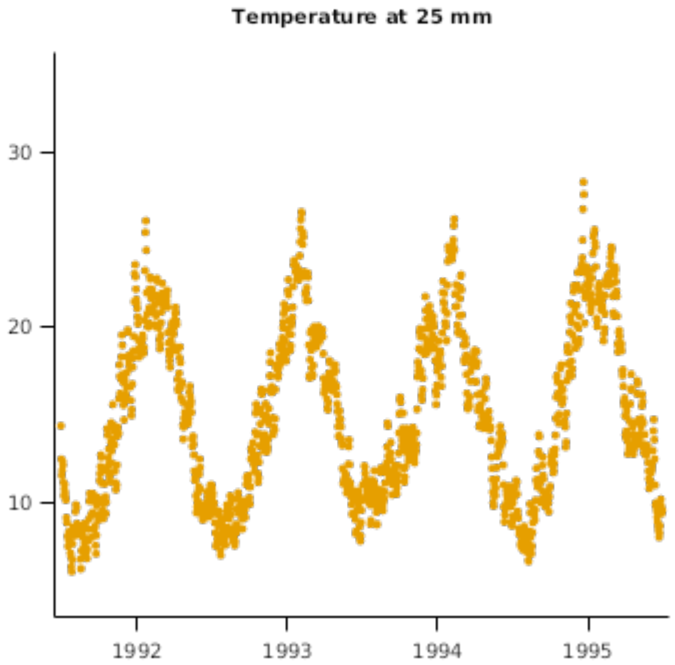


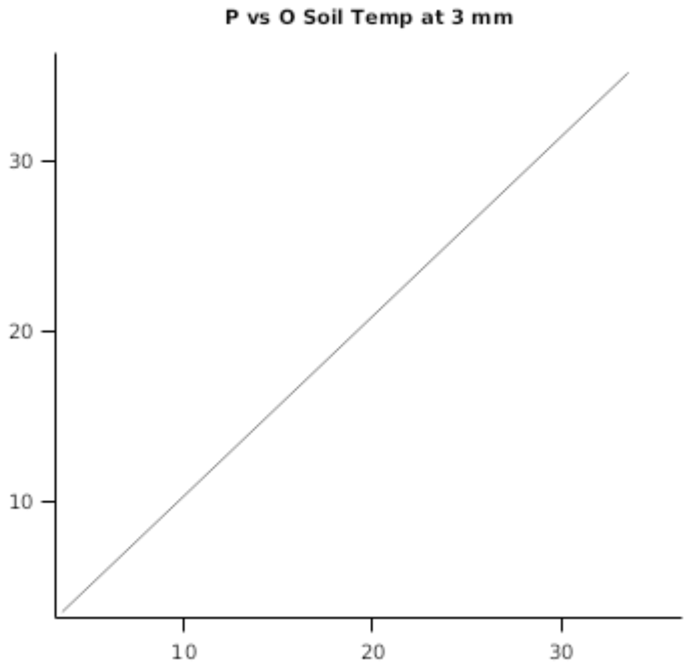
Cavendish 250mm

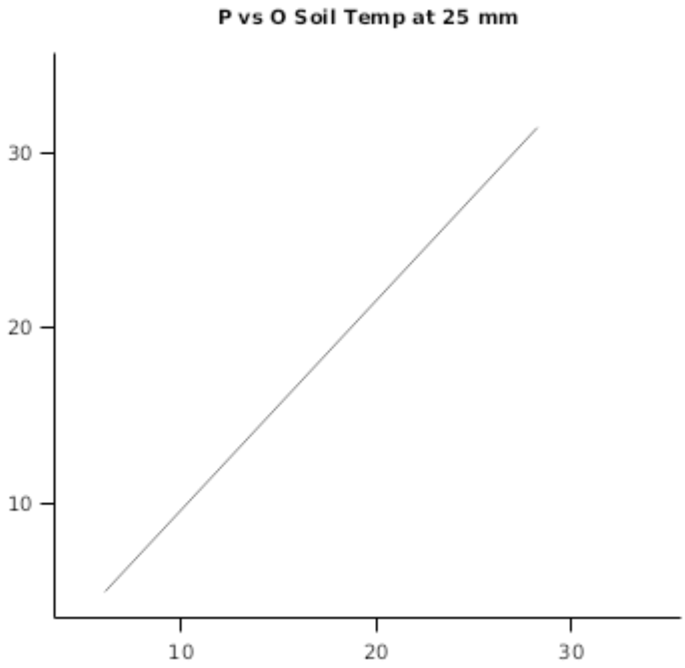
6.2 Wagga

Wagga





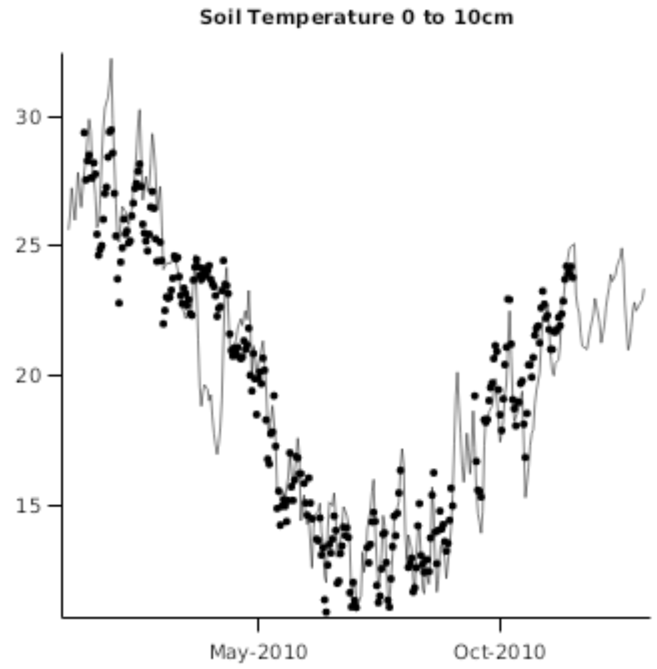


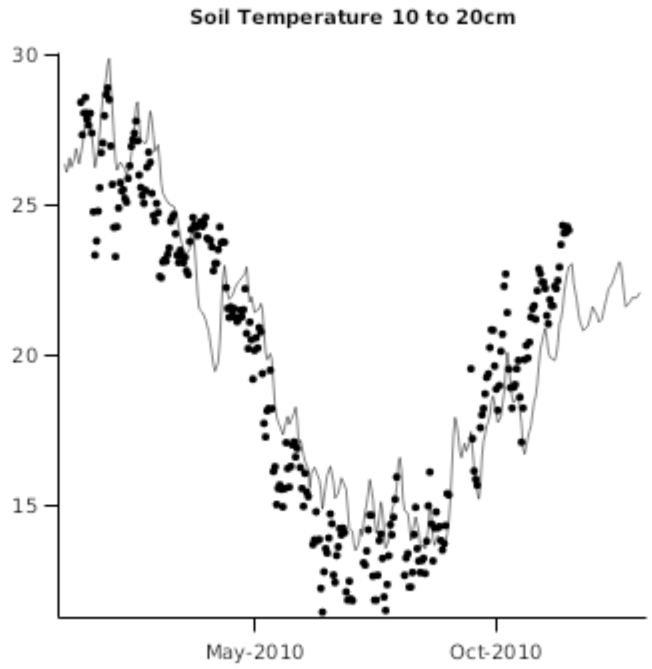


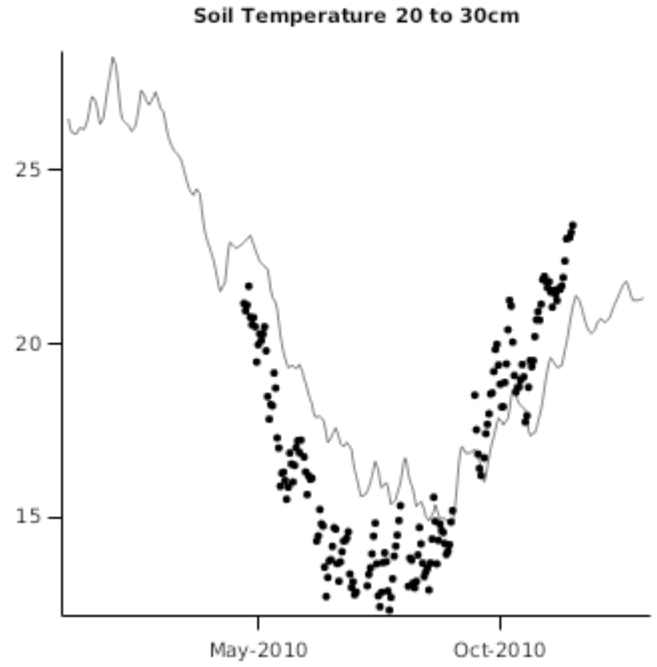
6.3 Norwin

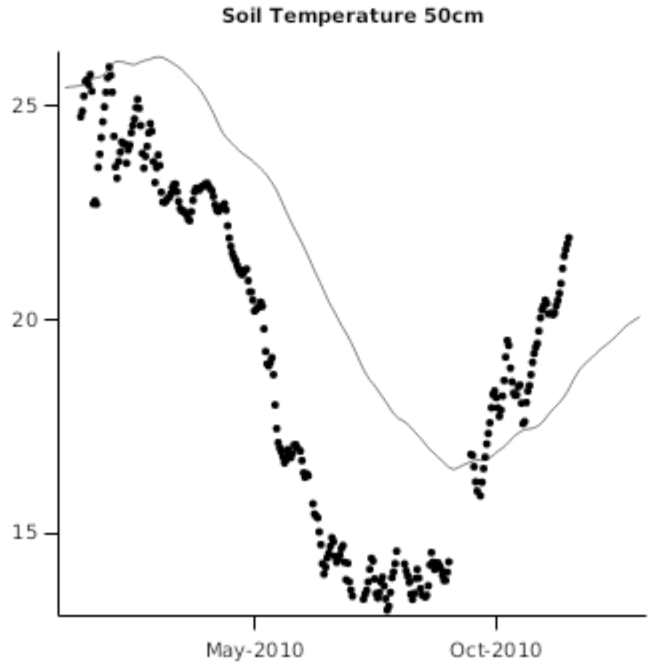
Note that there is limited weatehr data available for this simulaiton. It is likely that the poor performance at 0.5 m is at least partially due to the short run in to the simulation.

Norwin





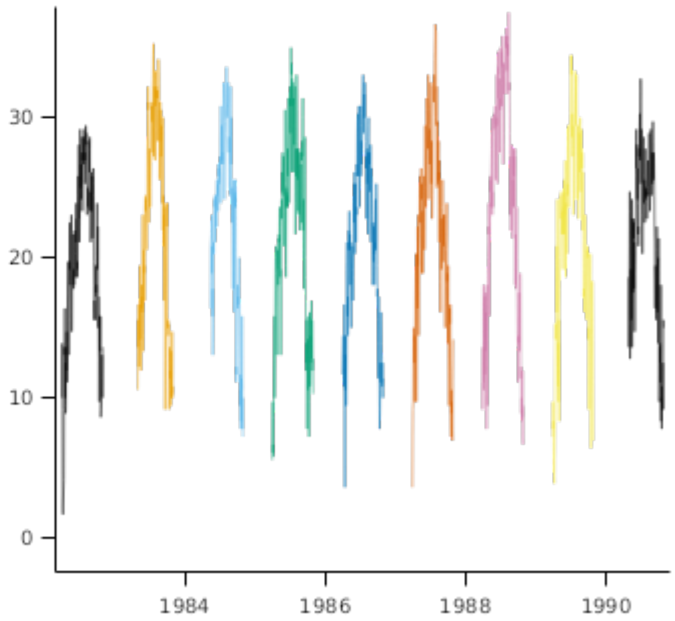




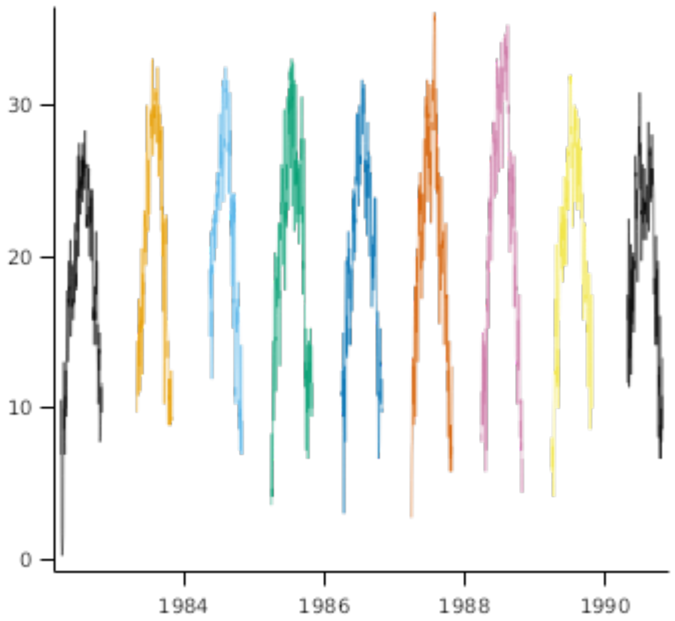
6.4 USA BareSoil

List of experiments.

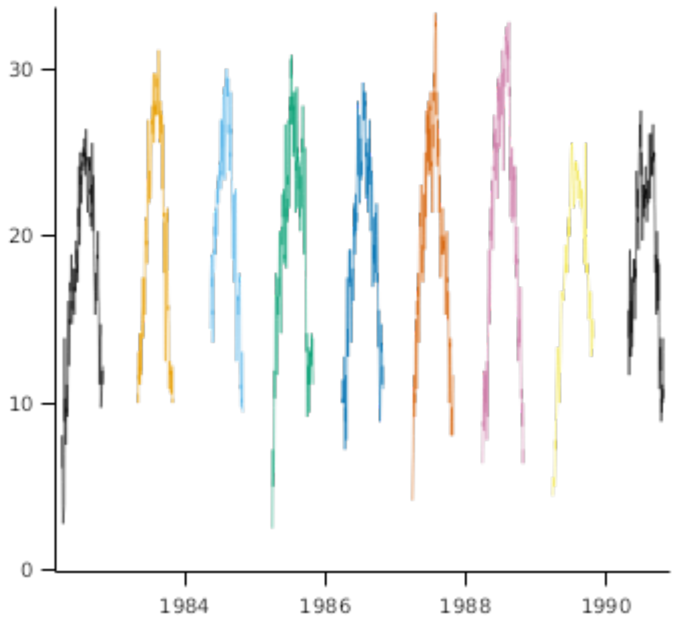
Experiment Name	Design (Number of Treatments)
ST	Year (9)



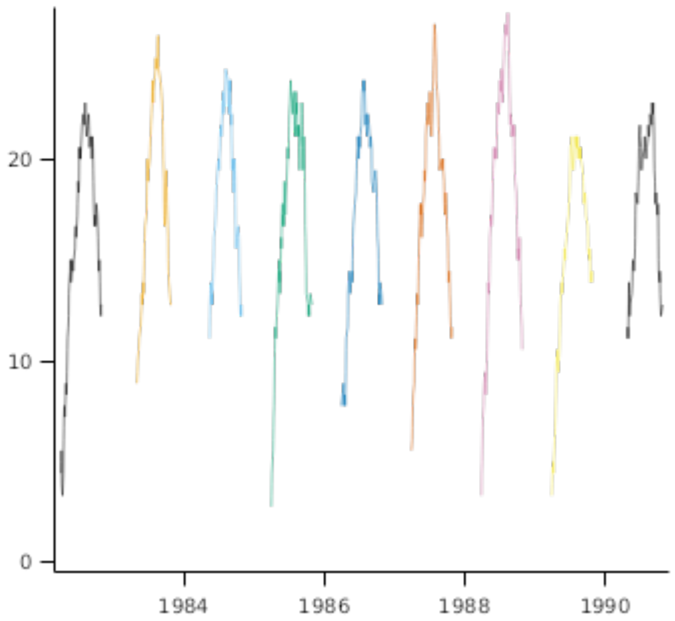
Temperature at 25 mm



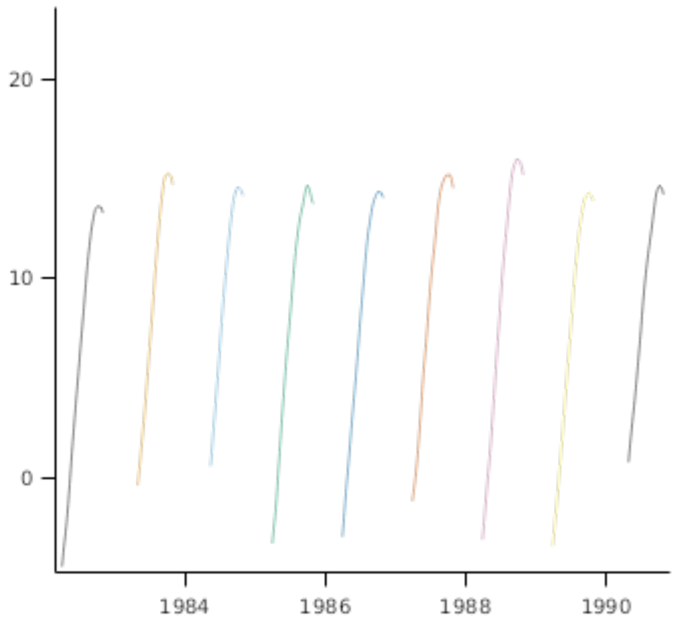
Temperature at 100 mm



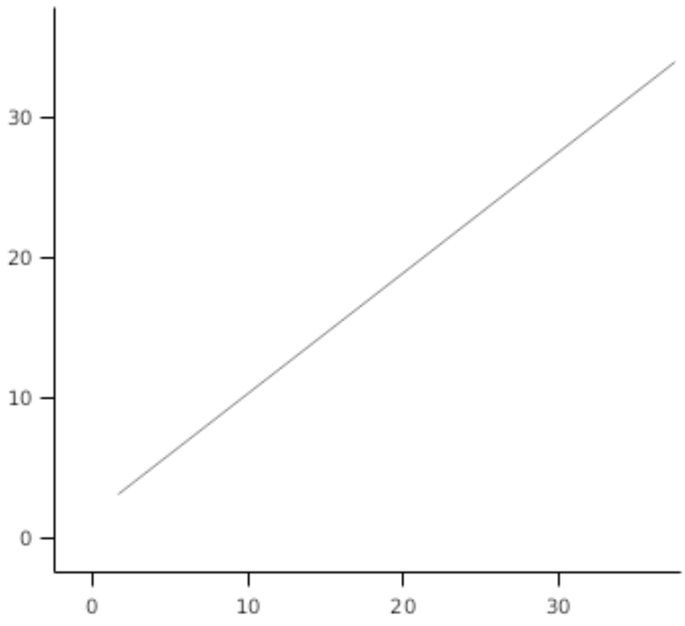
Temperature at 200 mm



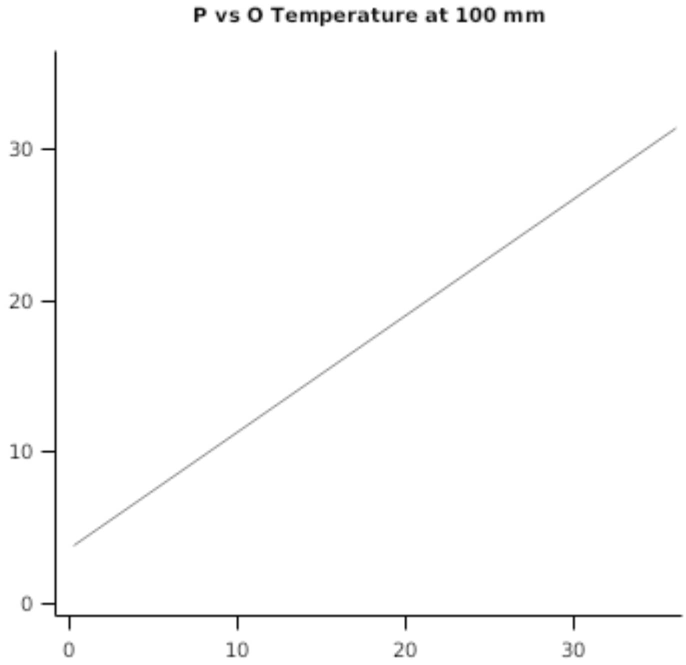
Temperature at 400 mm

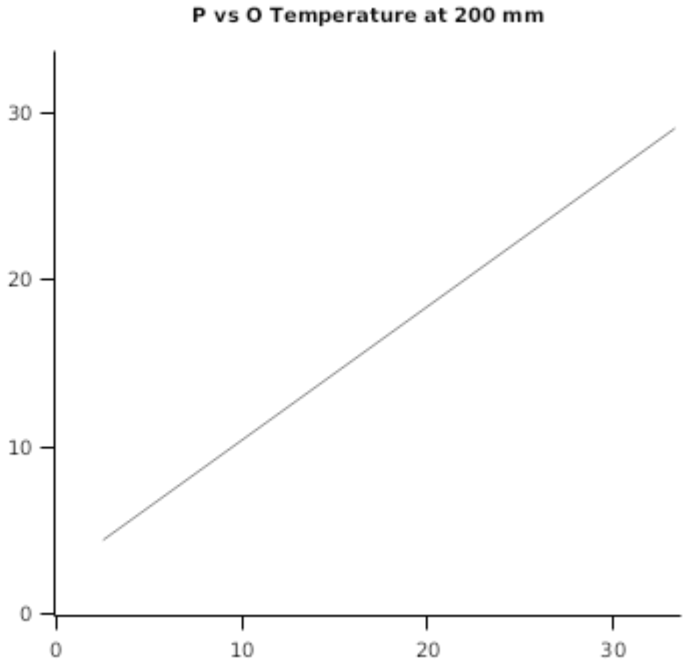


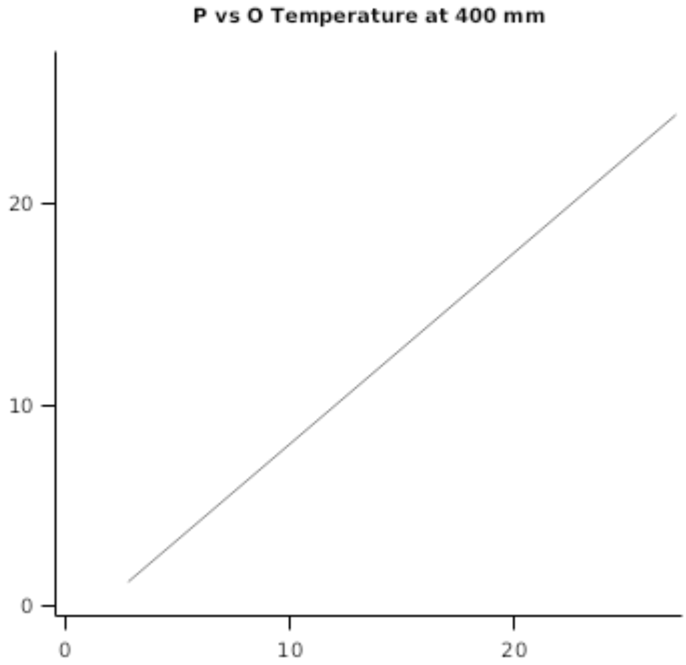
Temperature at 850mm

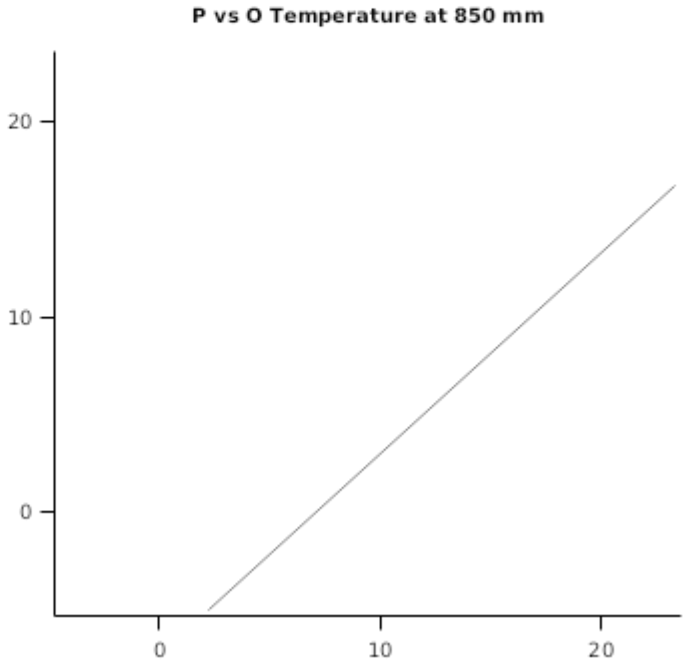


P vs O Temperature at 25 mm


P vs O Temperature at 100 mm

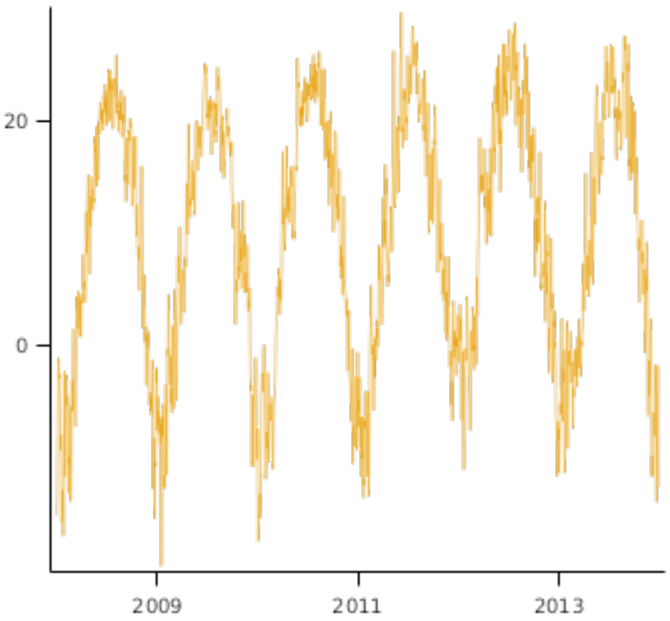

P vs O Temperature at 200 mm


P vs O Temperature at 400 mm

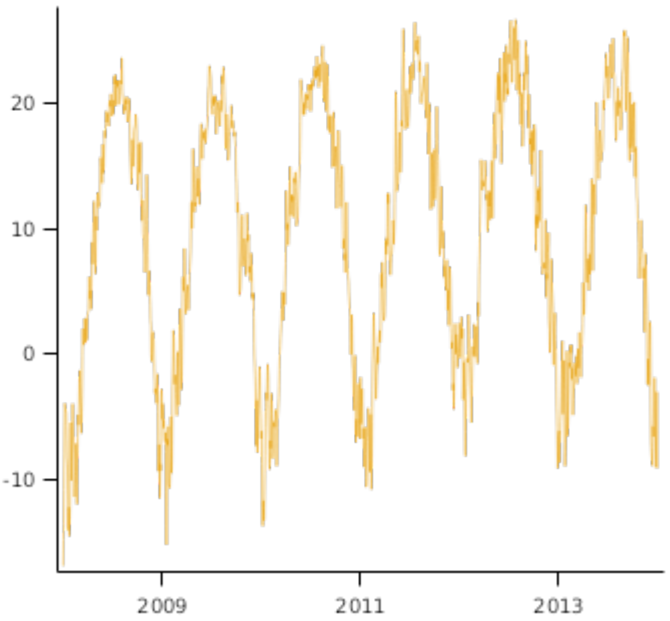

P vs O Temperature at 850 mm

6.5 USA CornSoybean

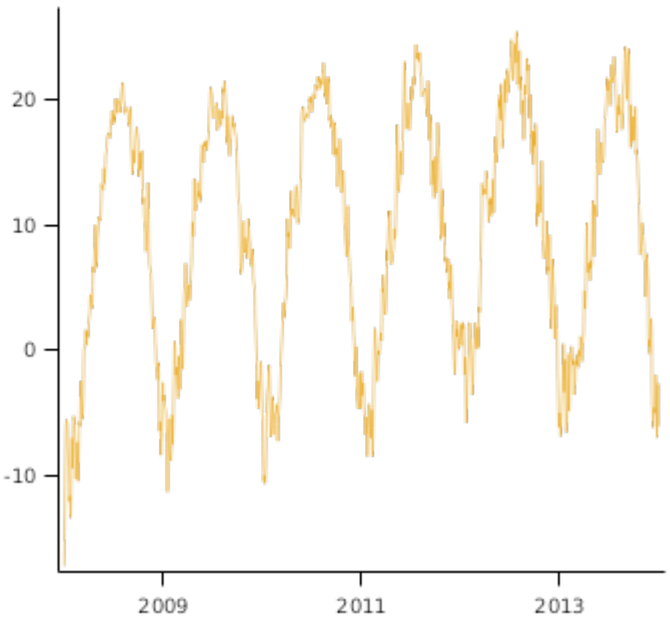
COBSSystemCS



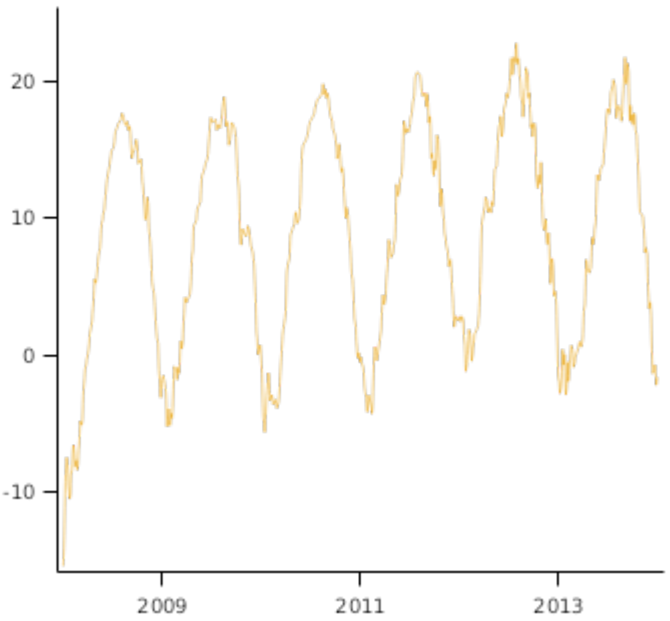
Temperature at 38 mm



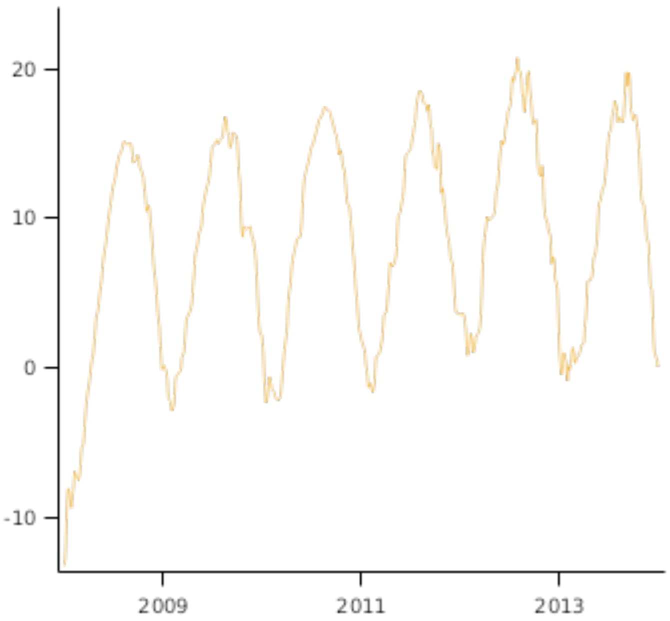
Temperature at 100 mm



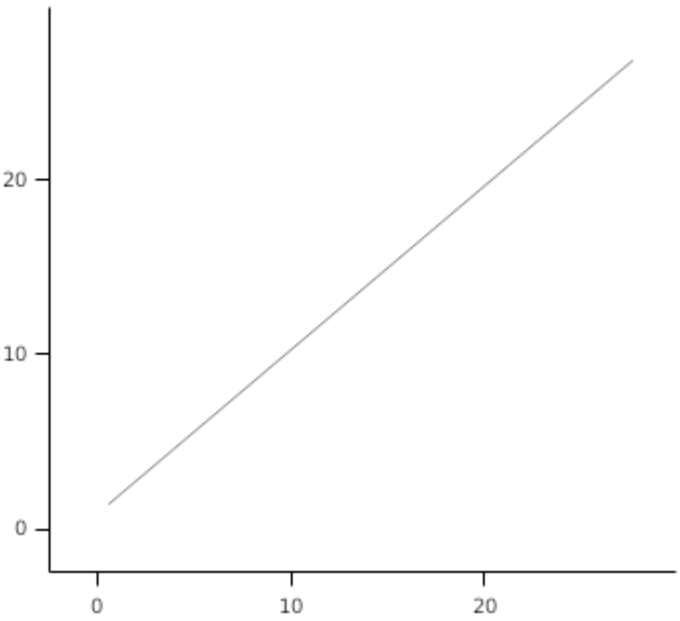
Temperature at 170 mm



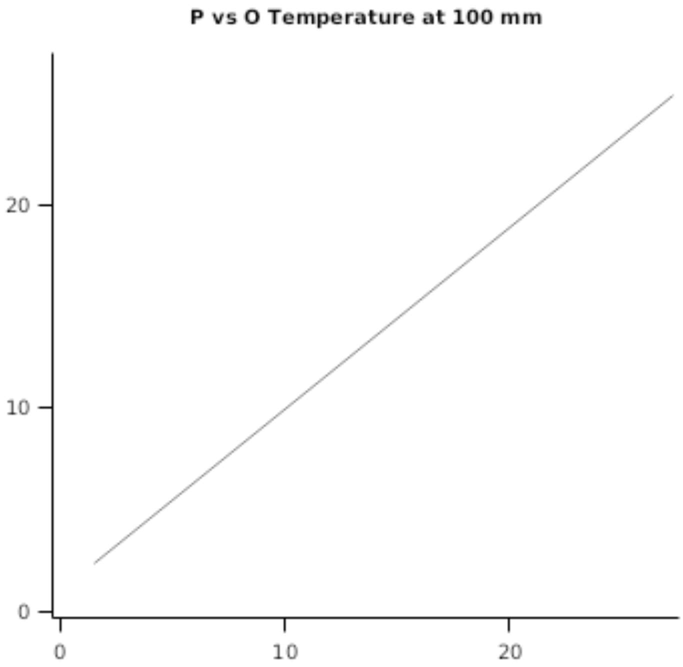
Temperature at 350 mm

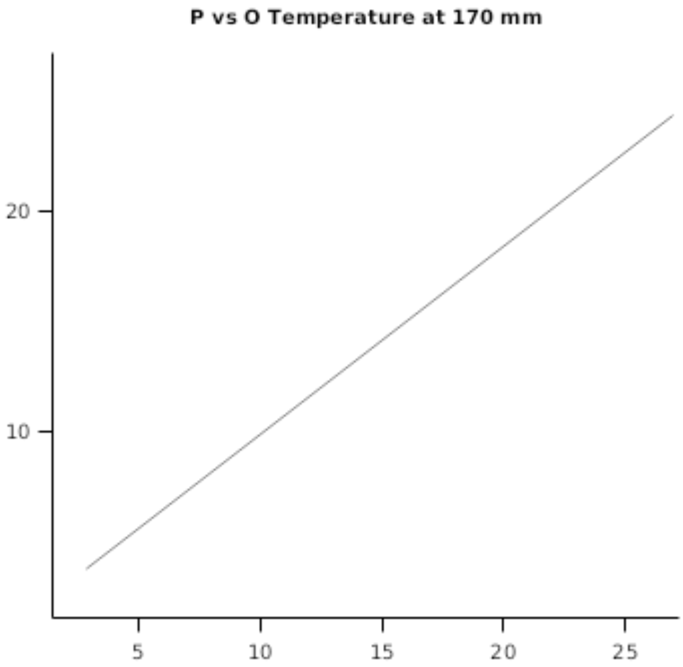


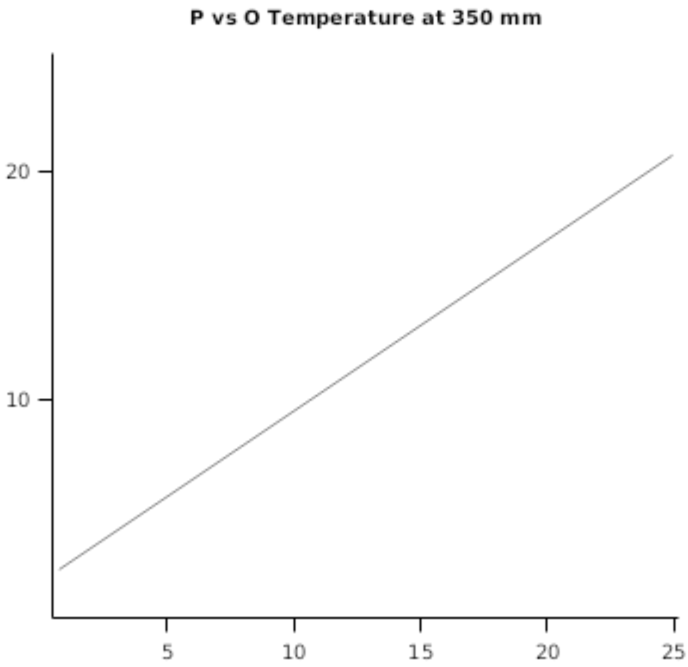
Temperature at 500 mm

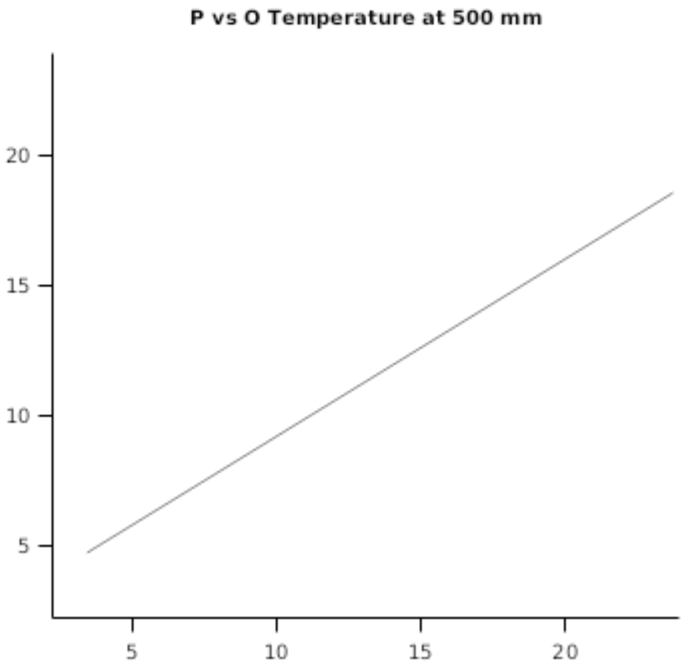


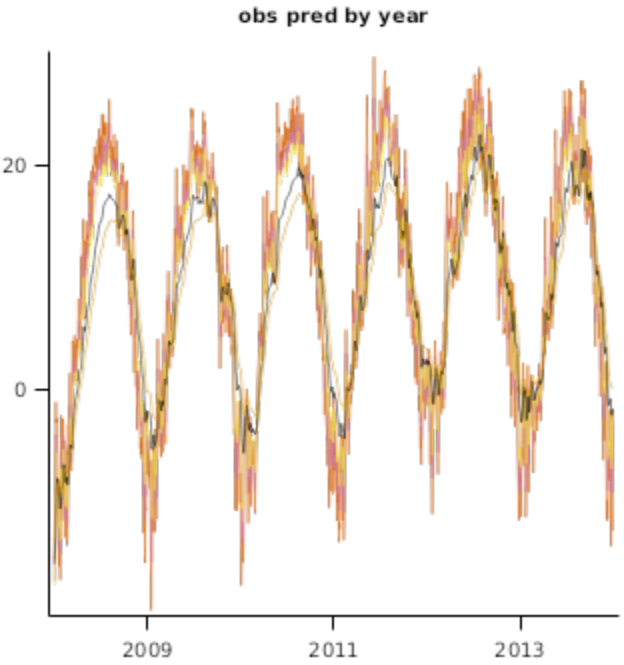
P vs O Temperature at 38 mm


P vs O Temperature at 100 mm


P vs O Temperature at 170 mm


P vs O Temperature at 350 mm


P vs O Temperature at 500 mm


obs pred by year

6.6 NewZealand

6.6.1 Simulating crop rotation under controlled conditions

Rob Zyskowski, Edmar I. Teixeira, Hamish Brown, Edith Khaembah, Rogerio Cichota
The New Zealand Institute for Plant & Food Research Limited, Private Bag 4704, Christchurch, New Zealand

6.6.2 Introduction

This is a simulation of a crop rotation consisting of a forage species, fodder beet (*Beta vulgaris* L.), grown over spring/summer and harvested in autumn, followed by a catch crop, oats (*Avena sativa* L.). The actual experiment was divided in two phases and was established at the rain shelter facility of Plant and Food Research, Lincoln, NZ. The experiment was designed to help develop the models for the respective plants and here they are used to further demonstrate that ApsimX can simulate water and nitrogen cycling in the field and then to examine whether catch crops are a good option for mitigating N leaching from forages.

Phase 1: Co-limitation of water and nitrogen on fodder beet physiology

- Irrigation: 2 treatments, nil or full irrigation (to match PET)
- Nitrogen: 3 treatments, 0 kg N/ha, 50 kg N/ha & 300 kg N/ha applied as dissolved urea with fertigator
- 25 or 100 kg N/ha applied after emergence
- 25 or 100 kg N/ha applied when canopy nearly reached full cover
- 100 kg N/ha applied a month after full cover

Phase 2: Ability of oats to act as catch-crops for N over winter/spring

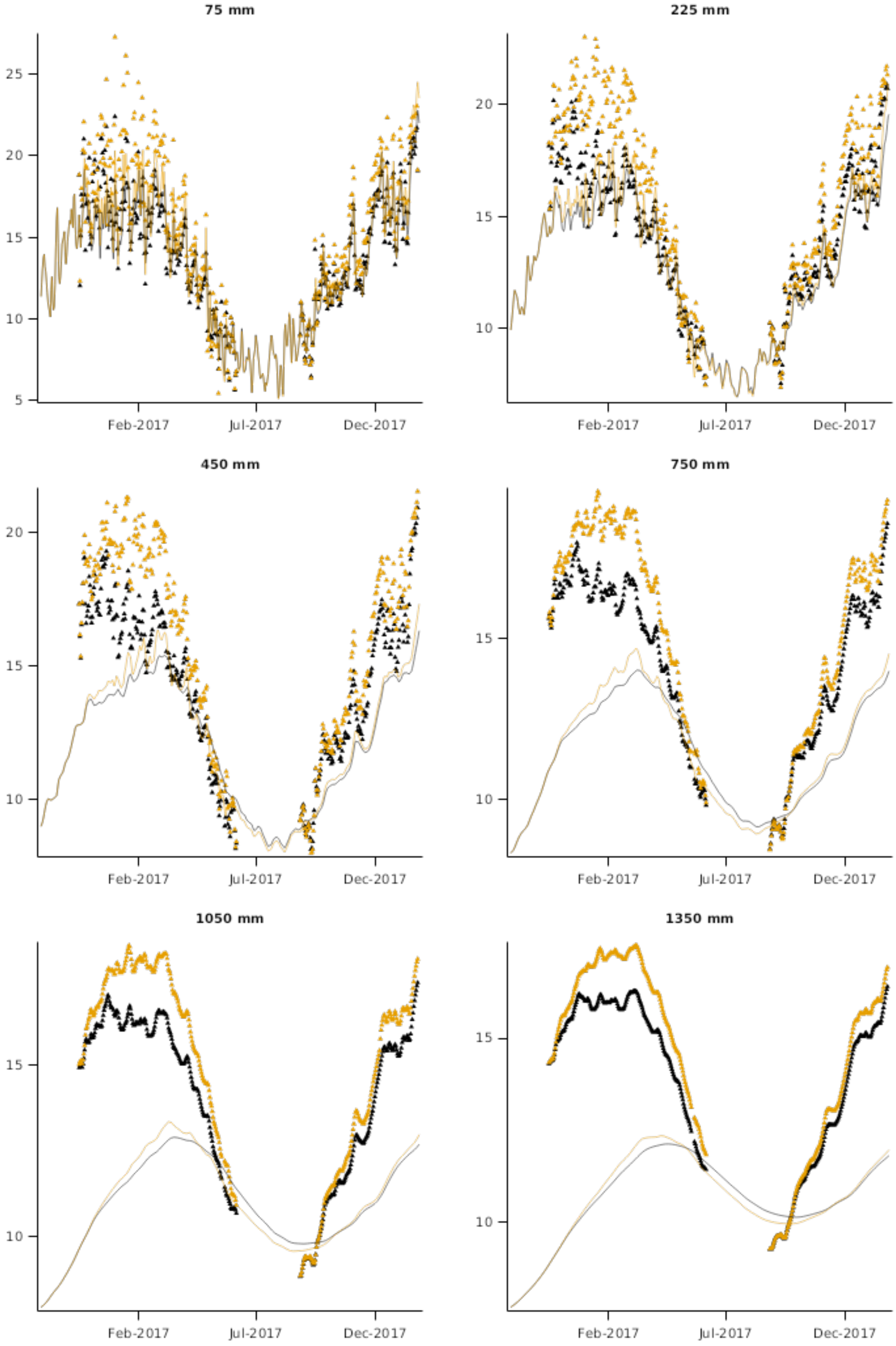
- Irrigation: 2 treatments, low (enough to keep plants growing) or full irrigation (to match PET)
- Nitrogen: 3 treatments, 80 kg N/ha, 125 kg N/ha & 320 kg N/ha at sowing (residual plus urea applied at sowing)

6.6.3 Acknowledgments

This work was a collaborative effort funded by the Sustainable Agro-Ecosystems (SAE) and the Forages for Reduced Nitrogen Leaching (FRNL) programmes. The experiment was setup and conducted by several people, including Brendon Malcolm, Emmanuel Chakwizira, Shane Maley, Mike George, Steve Dilon and Alexandre Michel, to whom we would like to express our gratitude.

List of experiments.

Experiment Name	Design (Number of Treatments)
LincolnRainshelter	Nit x Irr (2)


75 mm
25
20
15
10
5
Feb-2017
Jul-2017
Dec-2017
225 mm
20
15
10
Feb-2017
Jul-2017
Dec-2017
450 mm
20
15
10
Feb-2017
Jul-2017
Dec-2017
750 mm
15
10
Feb-2017
Jul-2017
Dec-2017
1050 mm
15
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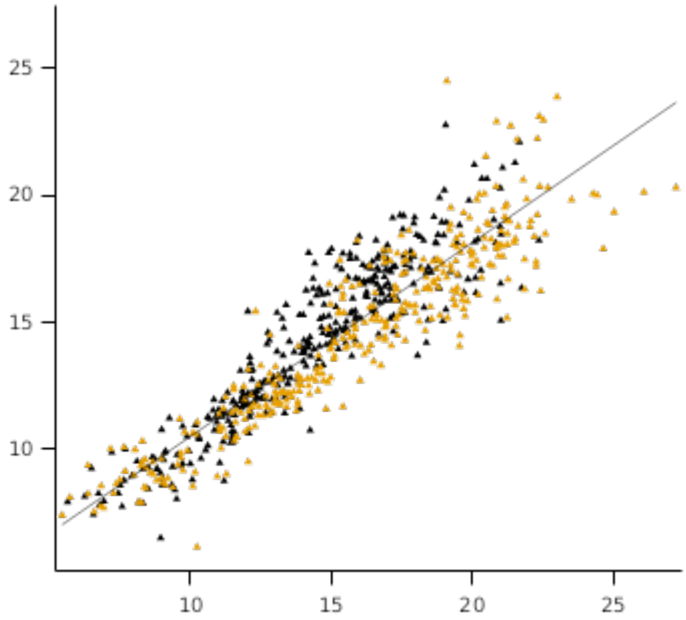
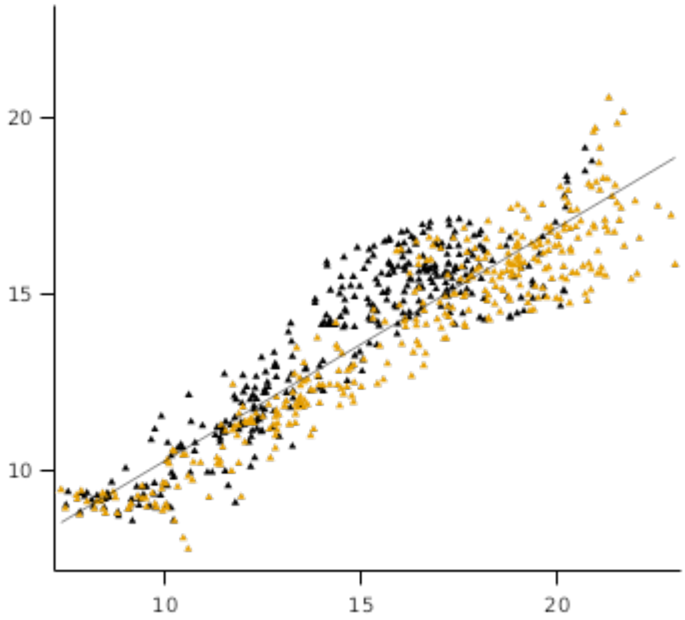
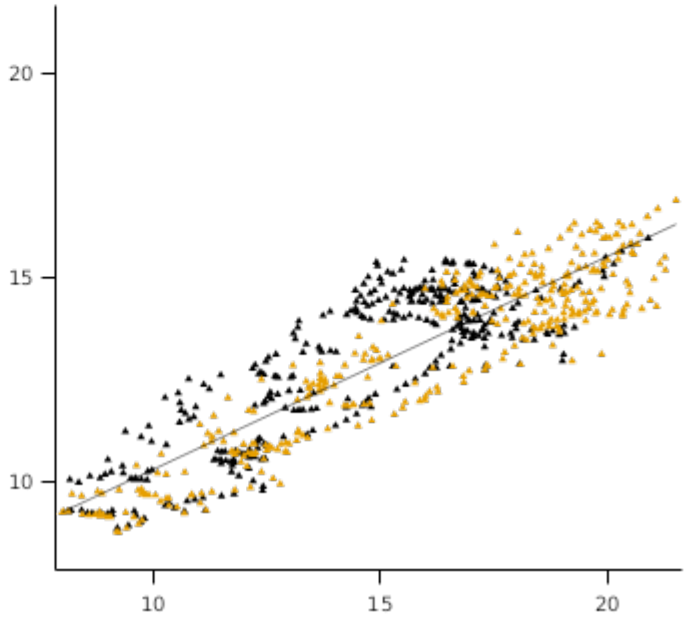
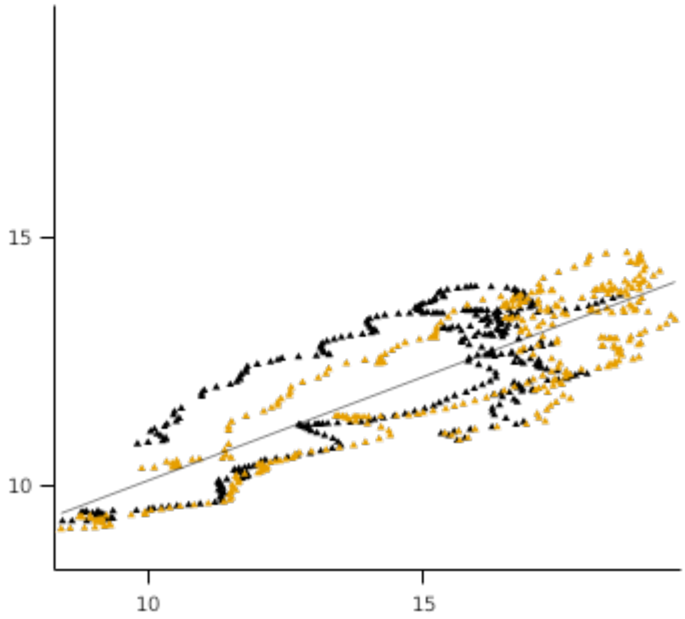
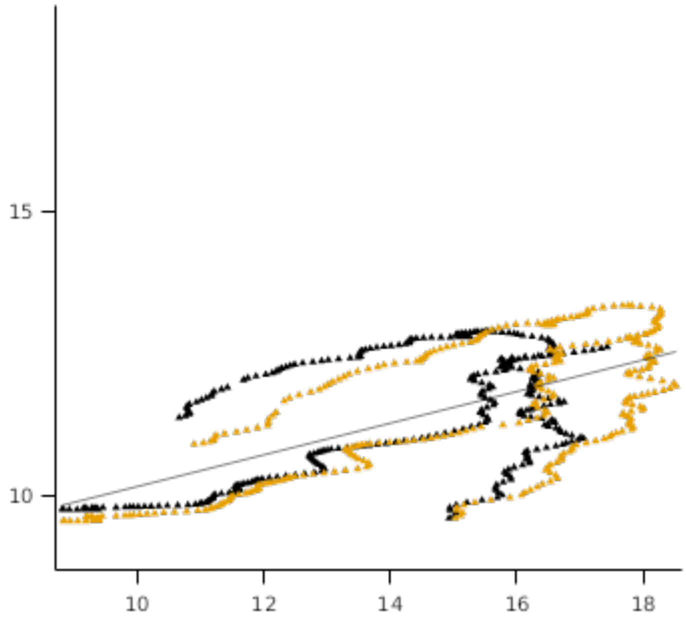
Feb-2017
Jul-2017
Dec-2017
1350 mm
15
10
Feb-2017
Jul-2017
Dec-2017

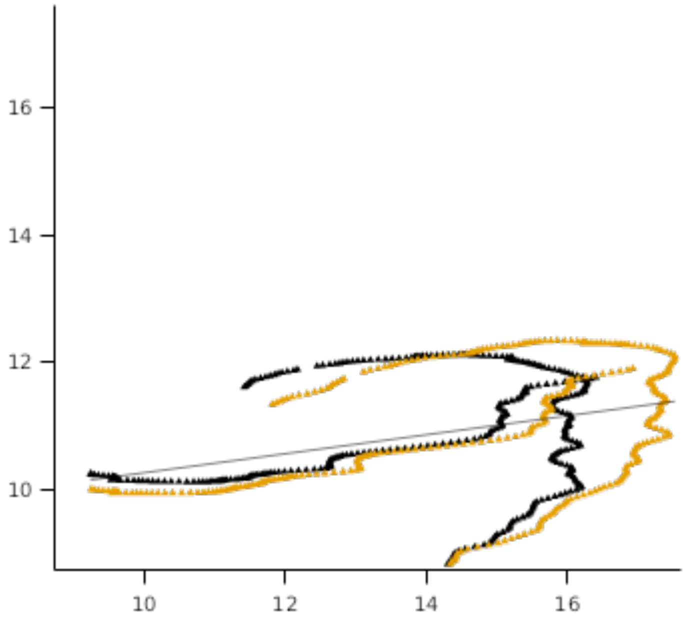

PredObs 75 mm


PredObs 225 mm


PredObs 450 mm


PredObs 750 mm


PredObs 1050 mm


PredObs 1350 mm

6.6.4 LincolnRainshelter

6.6.4.1 Management

Pre-experiment actions:
23/08/2016 - Oats harvested
02/09/2016 - Site irrigated with 25mm
05/09/2016 - Site ploughed
06/09/2016 - Site cambridge rolled
17/10/2016 - Site power harrowed
17/10/2016 - Rainshelter was rolled in
18/10/2016 - Fertiliser application (200kg/ha of KCl, 250kg/ha of Triple Super, 200kg/ha of NaCl and 30kg/ha of Boronate 15%)
18/10/2016 - Site cambridge rolled and harrowed

Experiment:

6.6.4.2 Fodder beet:

```
- Cultivar: Rivage
- Sowing density: 11 plants/m2
row spacing: 45 cm
depth: 15 mm

General actions:
18/10/2016 - Sowing
25/10/2016 - Irrigation of 5mm to all plots
27/10/2016 - Plants started to emerge
28/10/2016 - Irrigation of 5mm to all plots
28/10/2016 - First fertiliser application, 25kgN/ha of urea_N to the 50kg/ha plots and
100kgN/ha o the 300kg/ha plots
23/11/2016 - Irrigation treatments started
18/01/2017 - Second fertiliser application, 25Nkg/ha of liquid urea_N to the 50kg/ha
plots and 100kgN/ha to the 300kg/ha plots
15/02/2017 - Final fertiliser application, 100Nkg/ha of liquid urea_N to the 300kg/ha
plots
17/05/2017 - Plots harvested
```

Intercrop actions:
19/05/2017 - All crop residues removed
25/05/2017 - Dryland plots irrigated with 100mm, over two days
29/05/2017 - Dryland 300N plot irrigated with 64.0mm 30/05/2017 - Dryland 0N and 50N plots irrigated with 30.3 and 51.0mm 22/06/2017 - Site topped with maxitell
30/06/2017 - Site cambridge rolled
30/06/2017 - Rainshelter was rolled off (but it was put on in a few occasions)

6.6.4.3 Oats:

```
- Cultivar: Milton
- Sowing density: 300 plants/m2
row spacing: 15 cm
depth: 45 mm

General actions:
05/07/2017 - Sowing
05/07/2017 - Fertiliser application (400kg/ha Potash, Urea: treat4=40kgN/ha,
treat5=85kgN/ha, treat6=270kgN/ha)
24/07/2017 - Plants started to emerge
11/09/2017 - Irrigation started in treatements 4, 5, and 6
06/11/2017 - Irrigation extended to all plots
04-09/01/2018 - Plots harvested
```

7 Effect of Soil Layering

SoilTemperature uses a numerical solution to the heat flow equation to find soil temperature at any depth. In principle, the numerical solution is sensitive to the layering but the extent of has not previously been tested in APSIM. Because the model will be used with both SWIM (thin, usually <5mm, surface layers) and SoilWater (thicker, usually >100 mm, surface layers) it is important to understand any sensitivity.

A simple simulation was set up using a ‘dummy’ model to hold soil water contents constant as the purpose here is to test the soil temperature simulation not the soil water simulation. Both simulations had soil extending to 1100 mm deep. The thin-layering simulation had 11 layers with the top layer 2 mm deep and with seven layers in the top 100 mm. The thick-layering simulation had six layers with only one layer in the top 100 mm – a value typical for simulations using SoilWater.

The simulation was further simplified by using synthetic weather that was a simple annual cycle with a superimposed fortnightly oscillation.

All temperatures plotted are the average temperature unless otherwise stated.

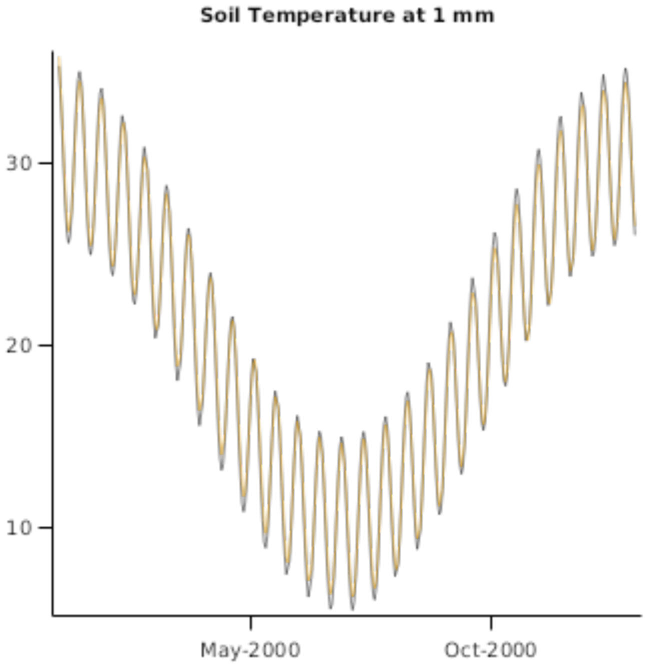
The first four plots below compare the simulated soil temperature across four depths with the thin layering in black and the thick layering in orange. Plots 5 to 8 show the 1:1 relationship between the two layering options. Note that the depths of 1, 8 and 15 mm all fall in the top layer of the thick-layering simulation but are in layers 1, 3, 4, and 8 of the thin-layering simulation. Plots 9 and 10 show the maximum simulated temperature at 1 mm deep.

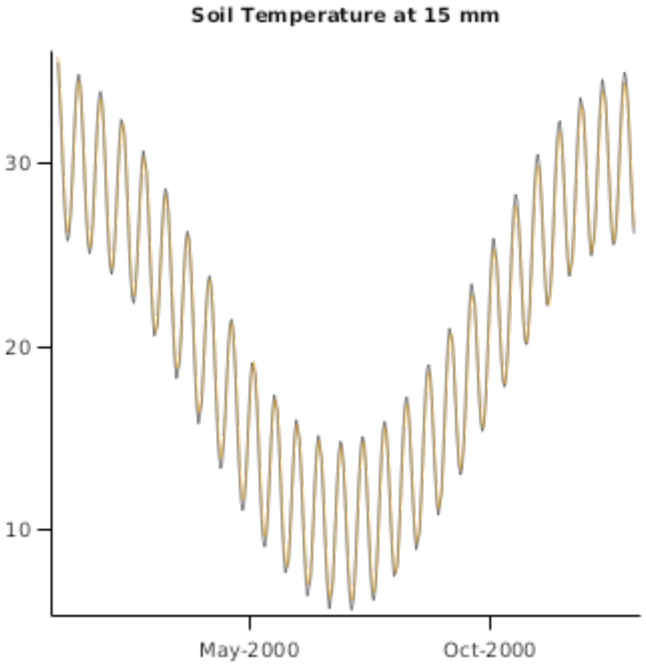
Overall, the simulations showed low sensitivity to the differences in layering (Plots 1-4). There was a greater difference in simulated maximum temperature than average temperature (plots 9, 10). For example, on 22 October the average soil temperature at 1 mm for the thin layering was 29 C v’s 28 for the thick layering (Plots 5 and 6). The differences in maximum temperature are greater than for average temperature. This is particularly evident in Plot 10 where the deviation at higher temperatures is about 3 C. It is possible that these differences may be important in future simulation purposes but these are minor differences when viewed from the perspective of must current uses.

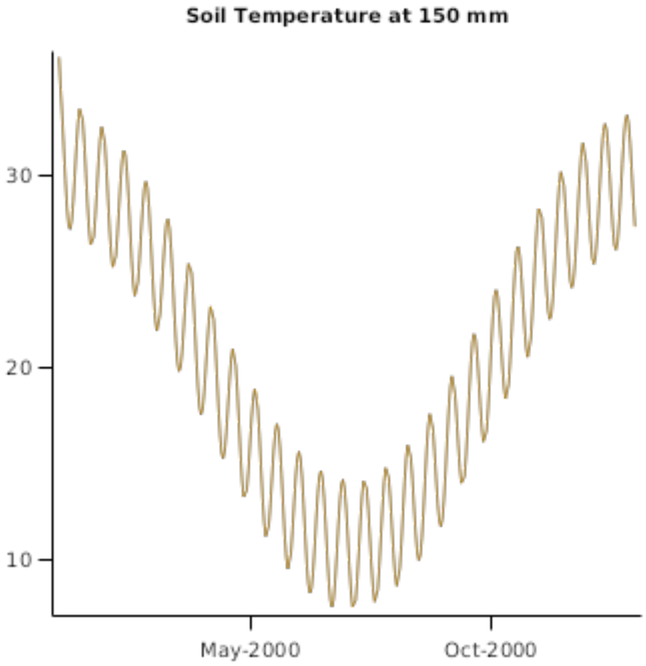
It must be emphasised that this test is on the soil temperature model only. Layering will have a substantial effect on soil water contents when a soil water simulation model is included in the simulation – and the differences in soil water content will feed through to greater differences in the simulated soil temperature. Users should be aware of this when deciding which soil water model to use.

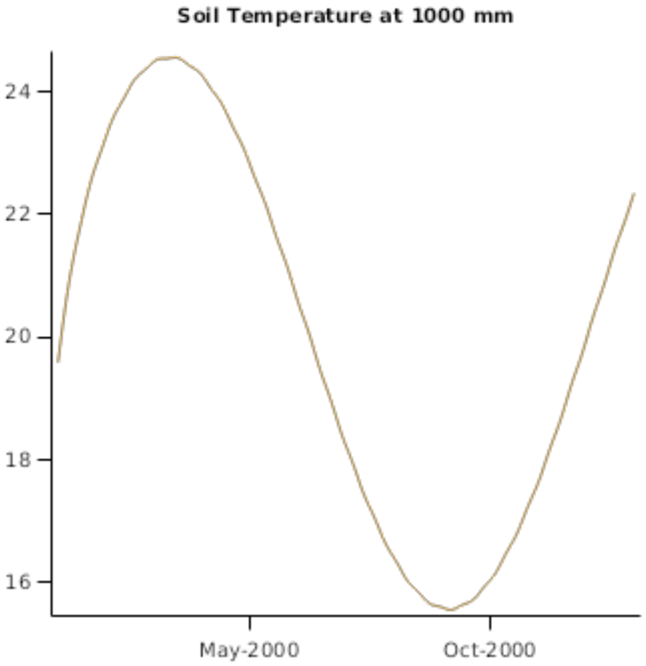
LayeringEffectThin

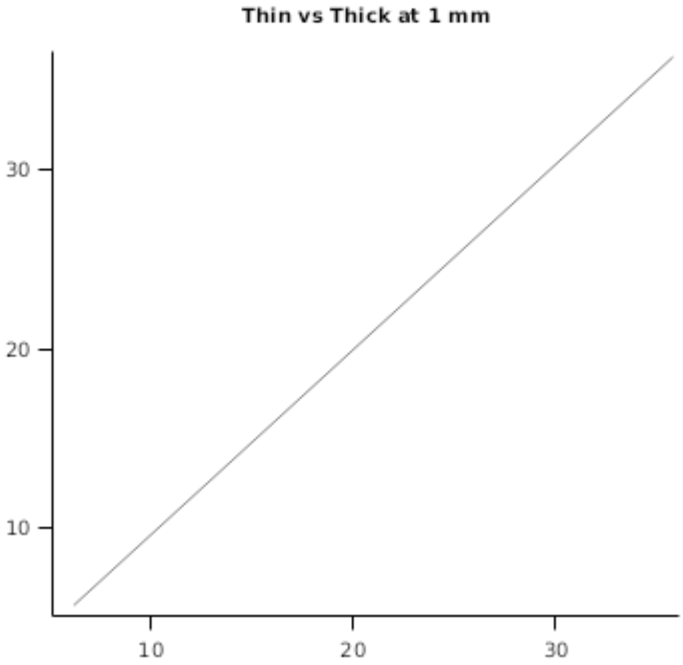
LayeringEffectThick

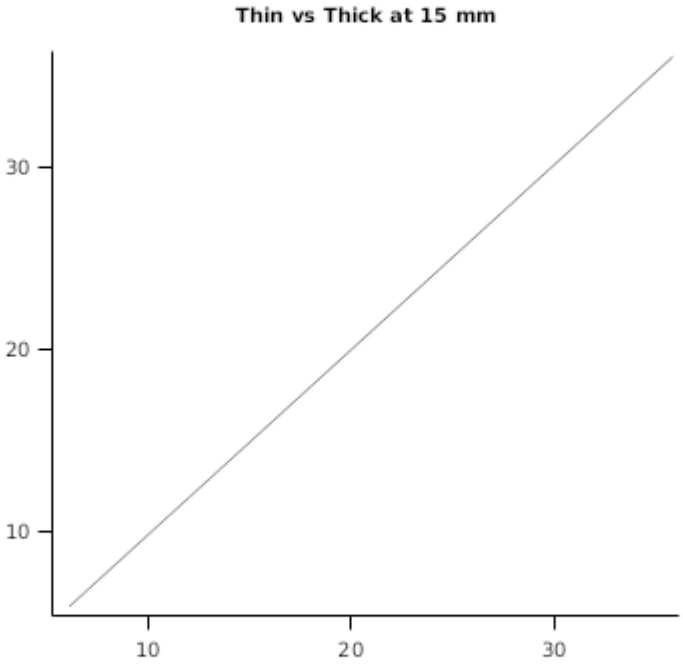

Soil Temperature at 1 mm

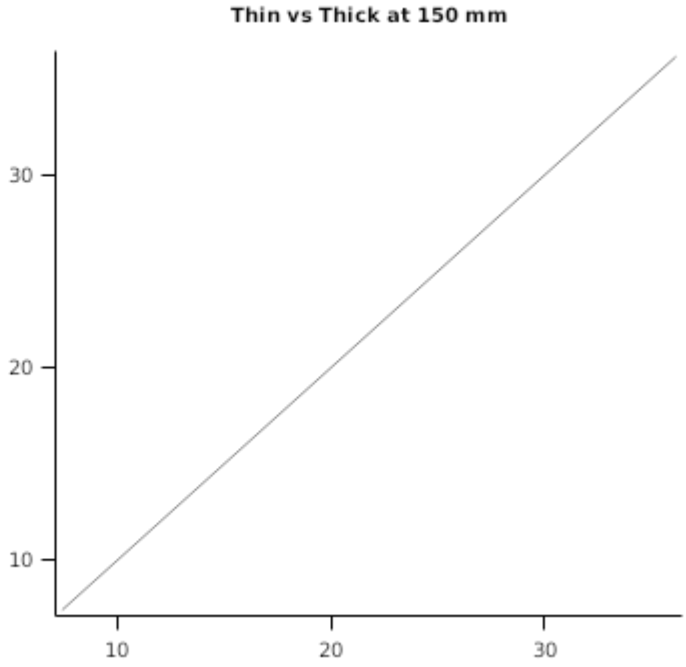

Soil Temperature at 15 mm


Soil Temperature at 150 mm

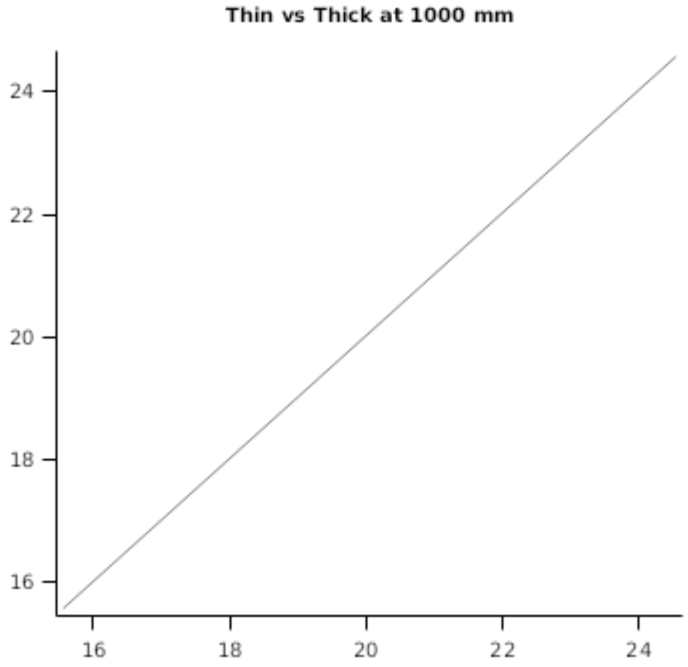

Soil Temperature at 1000 mm


Thin vs Thick at 1 mm

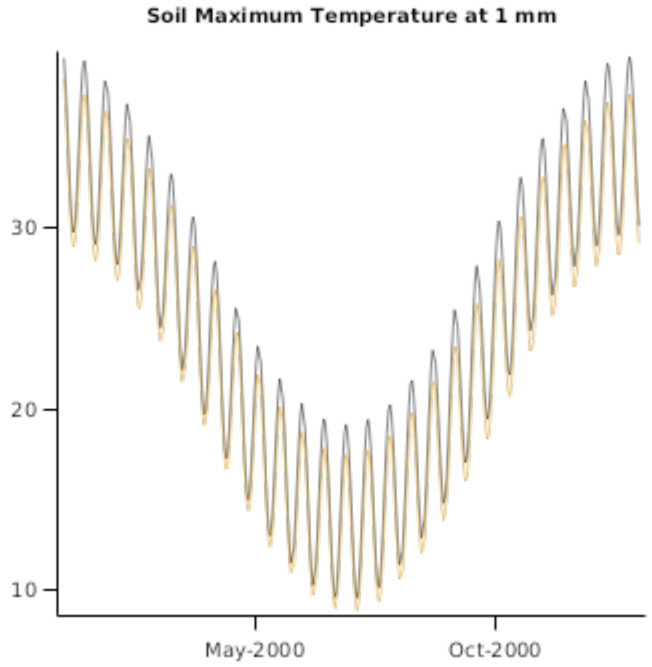

Thin vs Thick at 15 mm



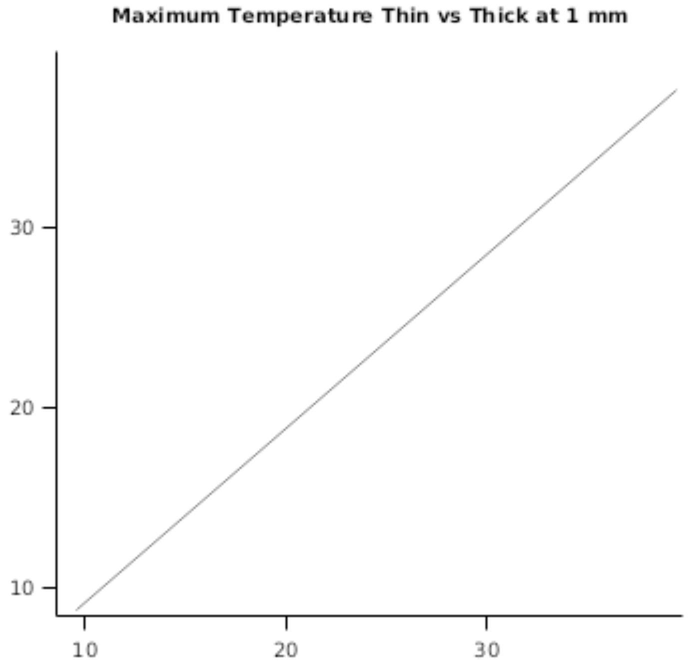
Thin vs Thick at 150 mm



Thin vs Thick at 1000 mm



Soil Maximum Temperature at 1 mm



Maximum Temperature Thin vs Thick at 1 mm

8 Initialisation Choices

SoilTemperature's numerical solution requires initial values of soil temperature by layer. These are not usually available from measurements so a scheme, based on a simplified analytical solution to the heat flow equation, has been implemented. Those estimated values are used by default unless the user adds in their own values.

Numerical solutions can take some time to 'forget' the initial conditions and the time to forget increases with depth. Simulations were set up to demonstrate this feature. The soil is a silt loam in a pasture system based at Lincoln, New Zealand. The simulation is set up with default initial conditions as well as two, deliberately bad, sets of initial temperatures – uniformly at -20.0 and 30.0 C.

The first four plots concentrate on the first two weeks of the simulation and the surface layers. The second four plots show simulated outputs deeper in the soil and over several years.

The deeper in the soil that the output is examined the longer it takes for the simulation to forget the initial temperatures. While we are not suggesting that initial conditions are routinely guessed as badly as these, it is important to note this effect when comparing against data. As a rough guide, if the depth of interest is in the top 300 mm then the 'run in' should be at least two weeks. At about 1 m deep the run in should be greater than six months and deeper than that it may be a year.

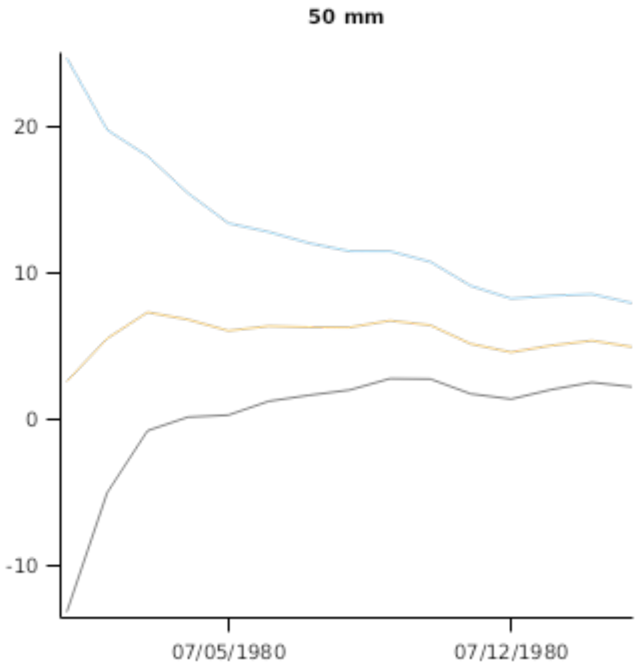
Note that these are worst-case scenarios and that other models, particularly SoilWater or SWIM and Nutrient, also require substantial run in times.

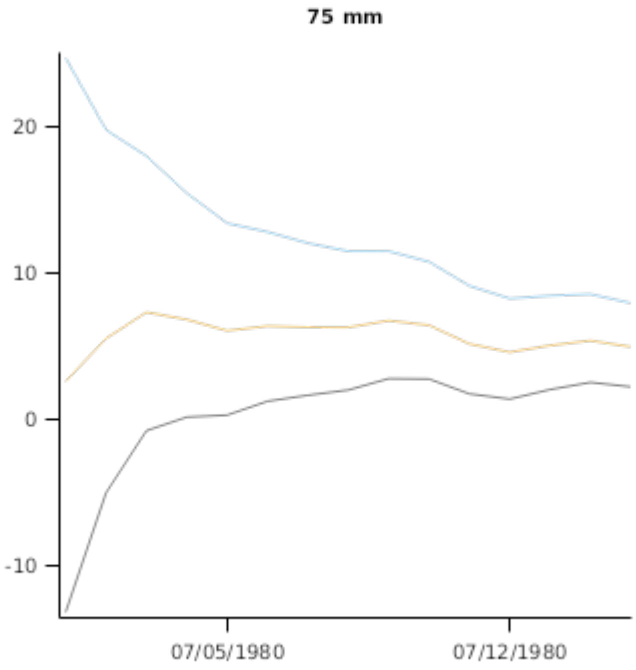
List of experiments.

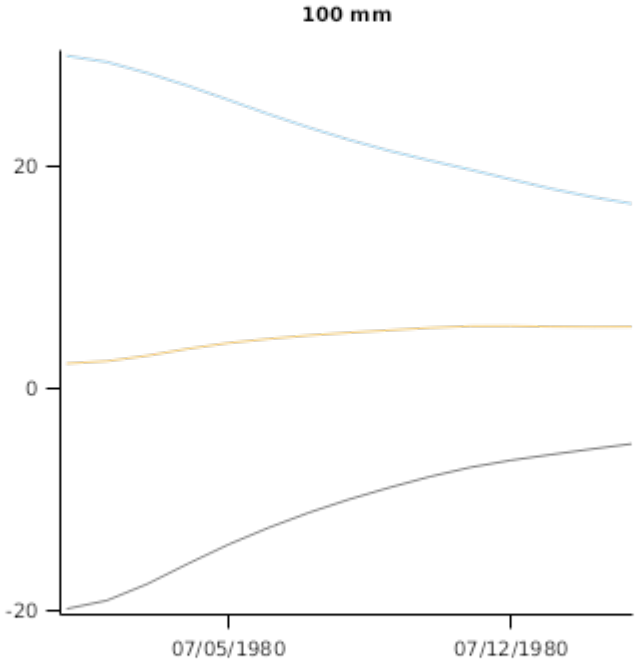
Experiment Name	Design (Number of Treatments)
InitialisationChoices	(3)

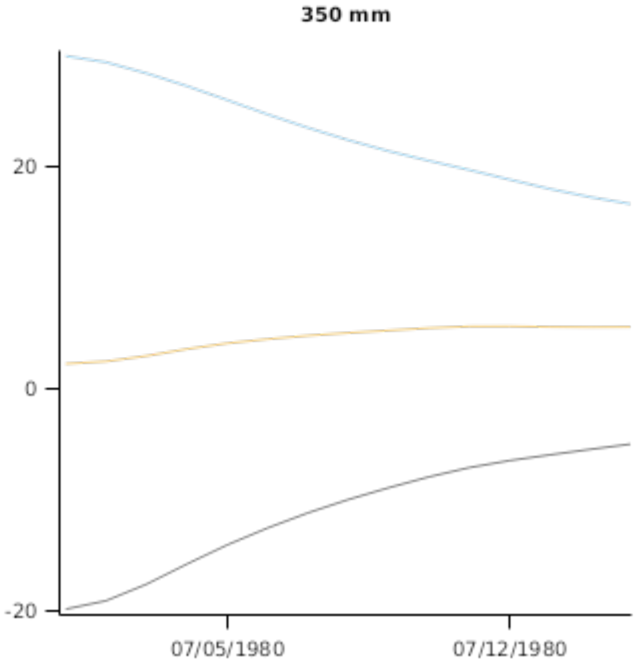
8.1 InitialisationChoices

8.1.1 Shortterm Plots

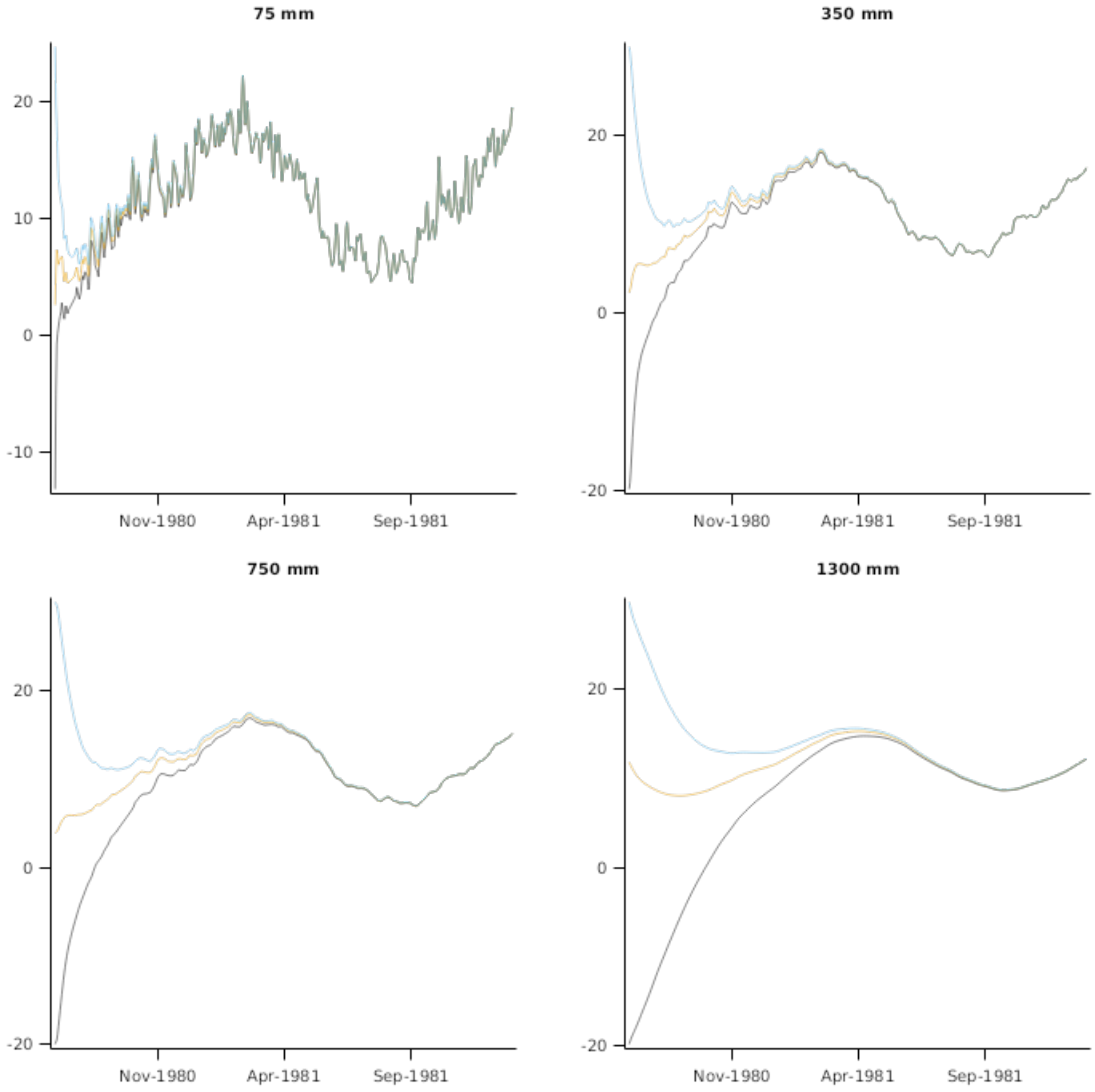








8.1.2 Longterm Plots

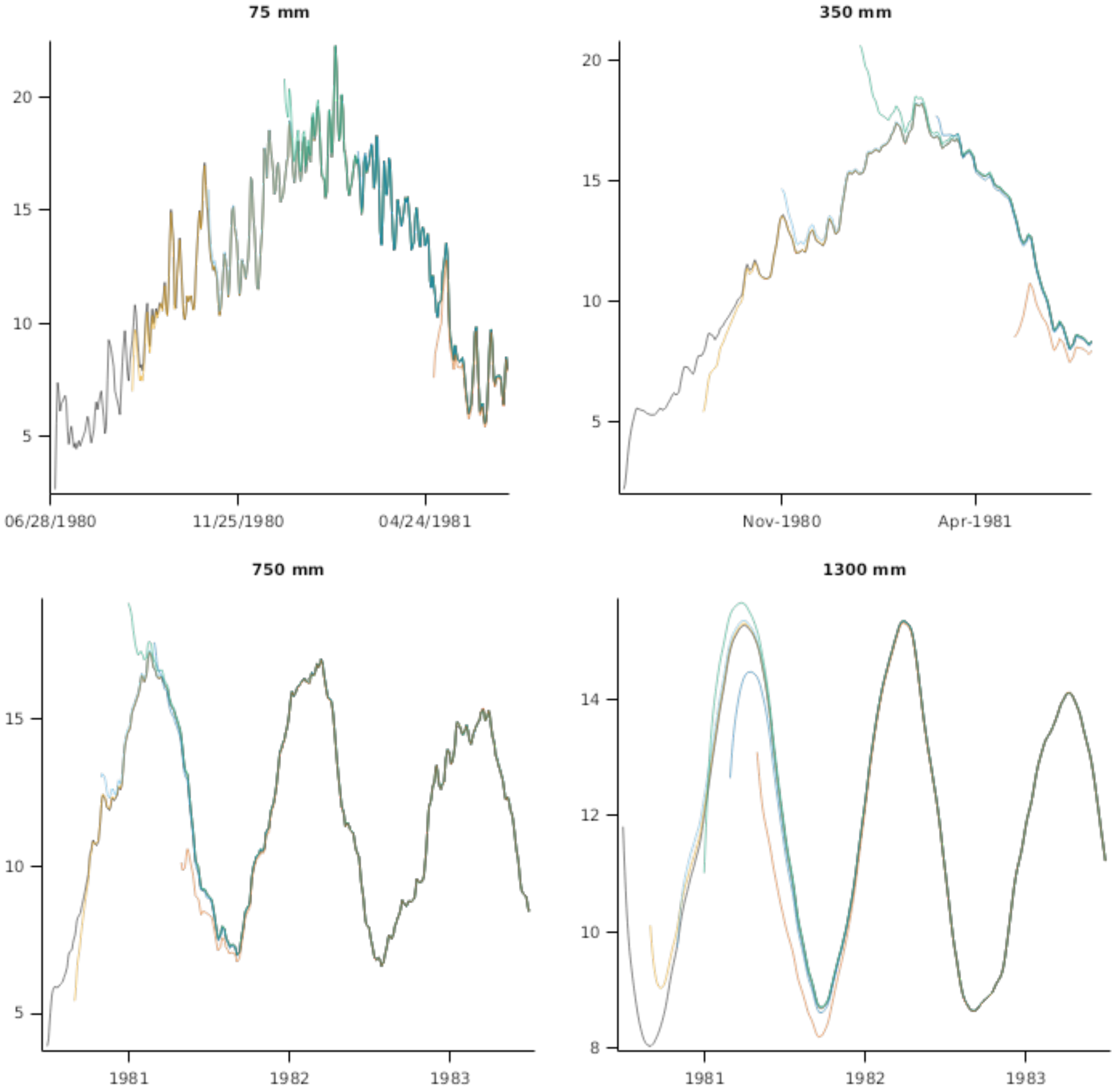


9 Initialisation Time of Year

The initialisation algorithm does a reasonable job of providing initial values but there is a lag once the simulation starts for the model to ‘forget’ the impact of the initial values. The deeper in the soil the longer that memory of the initial conditions is.

List of experiments.

Experiment Name	Design (Number of Treatments)
InitialisationTimeOfYear	Factor (6)



10 Resetting SoilTemperature

SoilTemperature allows the user to reset the simulated temperature at any time during the simulation with options of resetting to the values from the start of the simulation or to values specified by depth. Resetting is achieved using an Operations component.

The plots below have the temperature not reset at all (black) compared against a reset to the initial values on 1 September and a further reset to 6 C in every layer on 1 November (ochre). The commands to do the resetting are:

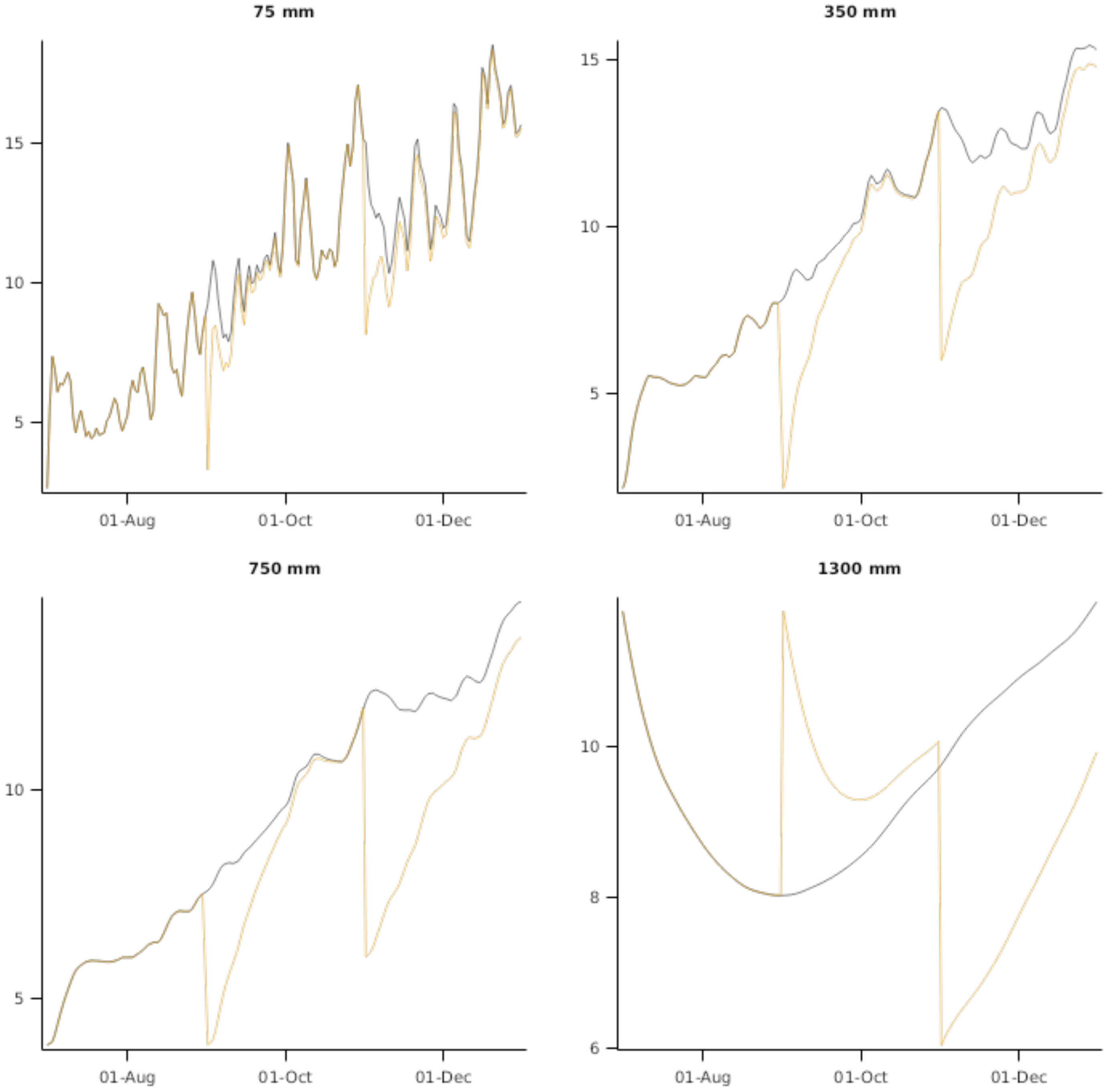
```
1980-09-01 [SoilTemperature].Reset()

1980-11-01 [SoilTemperature].Reset(6 6 6 6 6 6 6)
```

Note that if specific values are wanted (as opposed to the initial values), then the user must specify a value for each layer in a space-delimited format. If a LayerStructure is used in the soil then the layers in the reset command align to those in LayerStructure.

Further note that the values are reset at the start of the simulation day.

List of experiments.

Experiment Name	Design (Number of Treatments)
Resetting	(2)



11 SensibilityTests - Clay

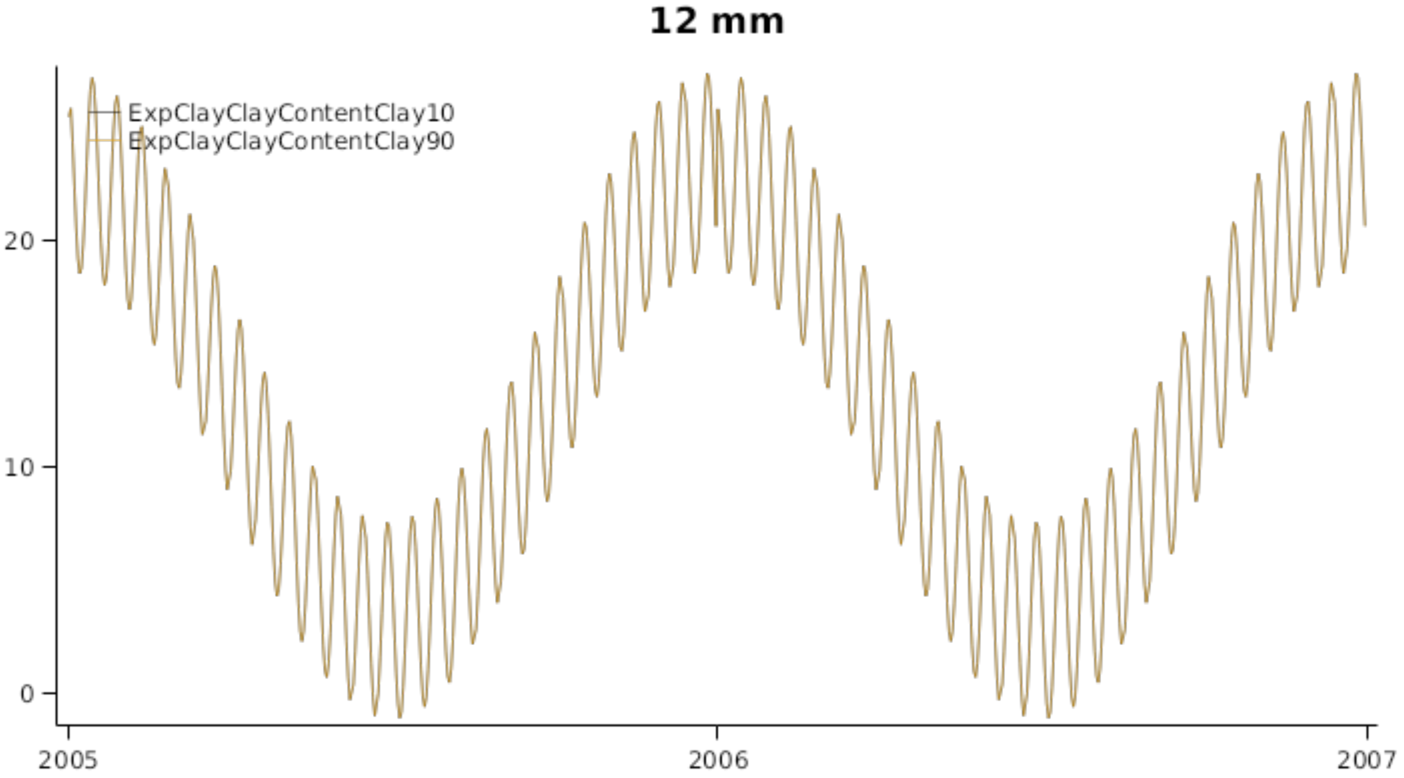
List of experiments.

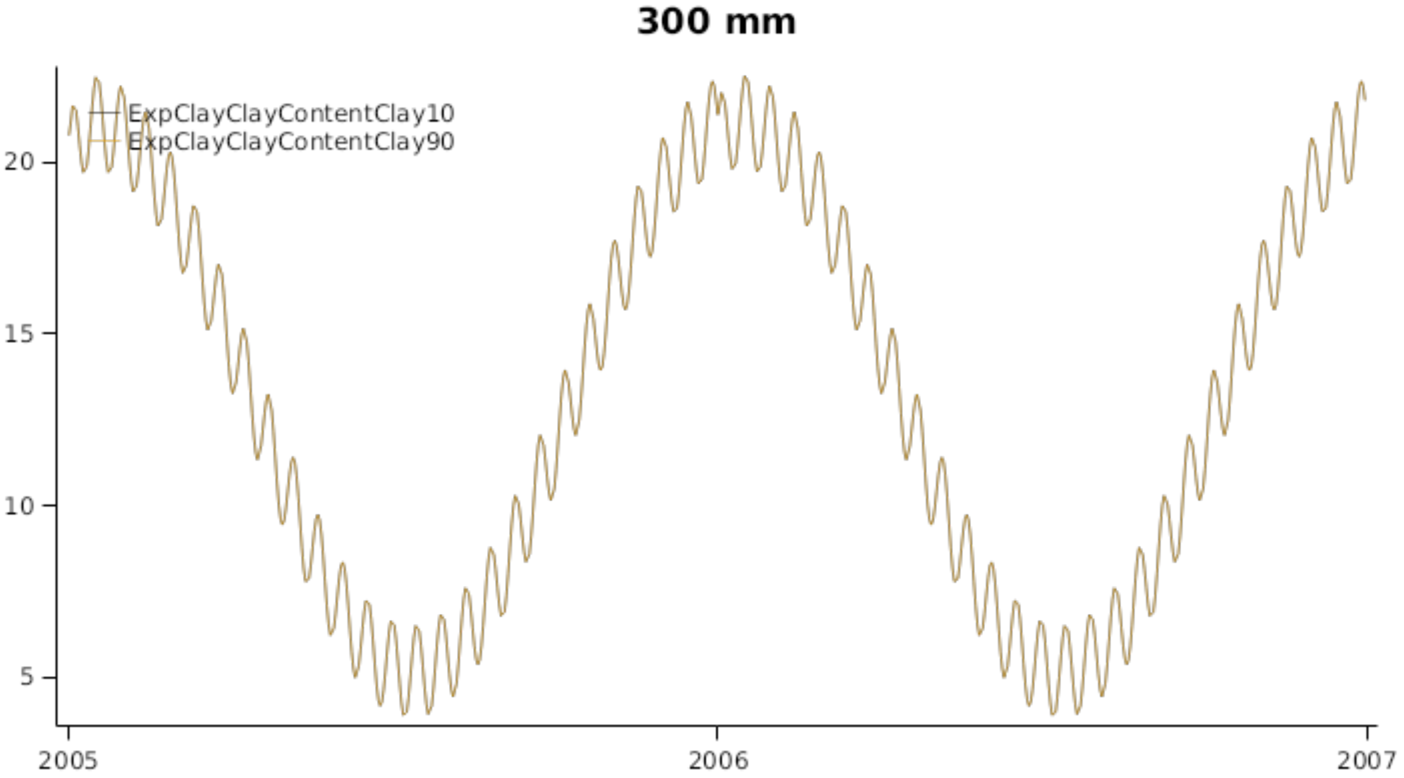
Experiment Name	Design (Number of Treatments)
ExpClay	ClayContent (2)

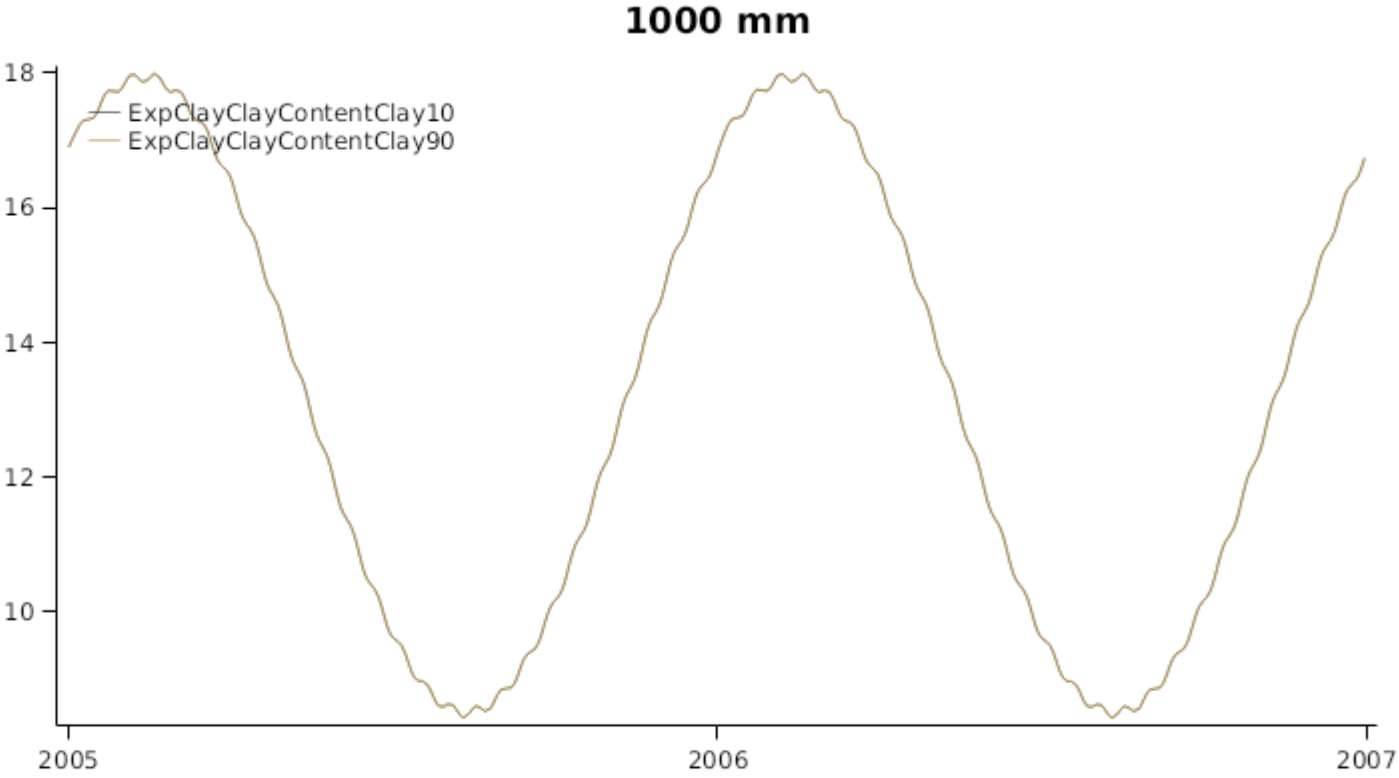
11.1 ExpClay

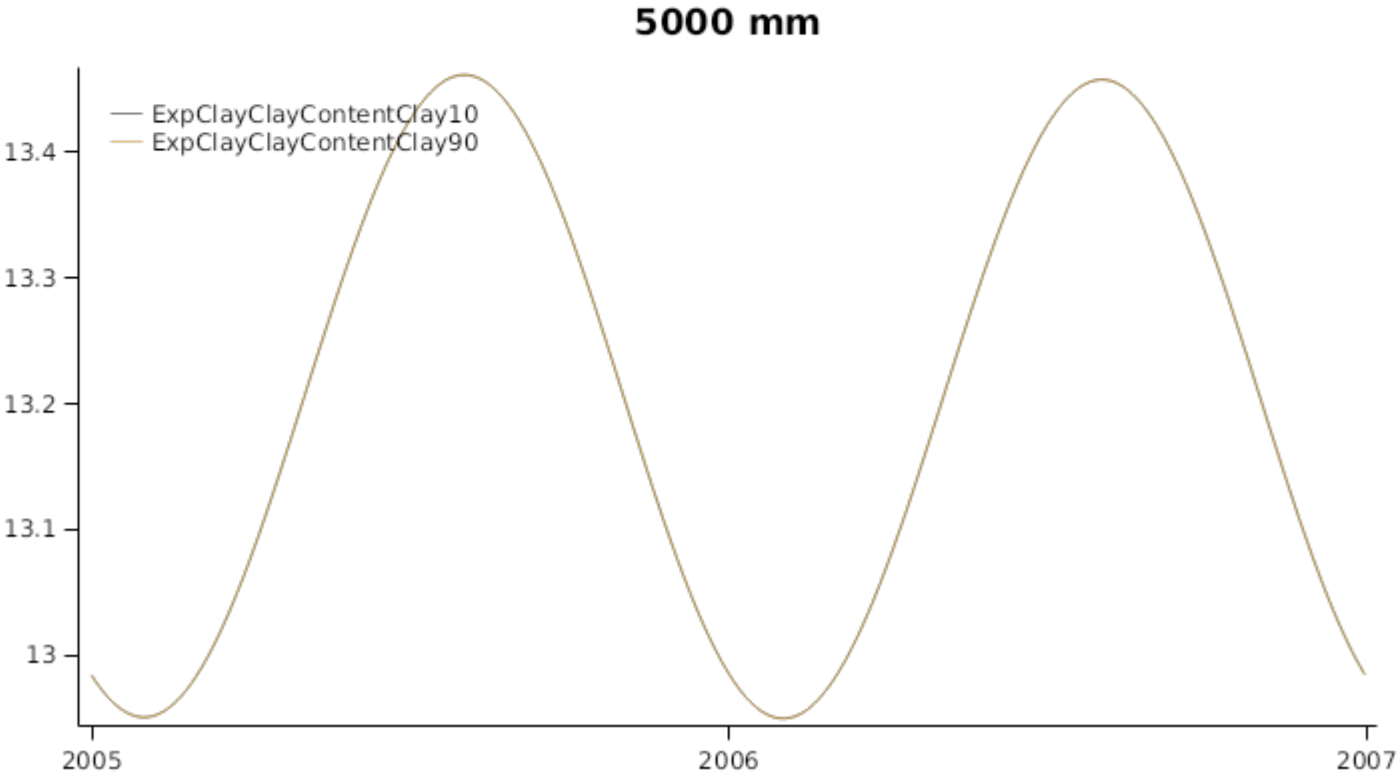
It is expected that soil temperature will show a sensitivity to soil properties, such as clay content. From theory, as the clay content increases then the ability to store heat increases. This effect should be evident when examining plots of soil temperature, comparing the effects of day-to-day air temperature oscillations and the annual oscillation cycle. A soil with higher clay content compared to one with a lower clay content, all other things including water content being held constant, should show a more muted effect of the oscillations and a greater delay between the peak air temperature and the peak in soil temperature. Shorter-term oscillations should also be dampened down more quickly with depth.

The plots below show these effects for a bare soil with a clay content of 10 and 90% held at a volumetric water content of 0.15.





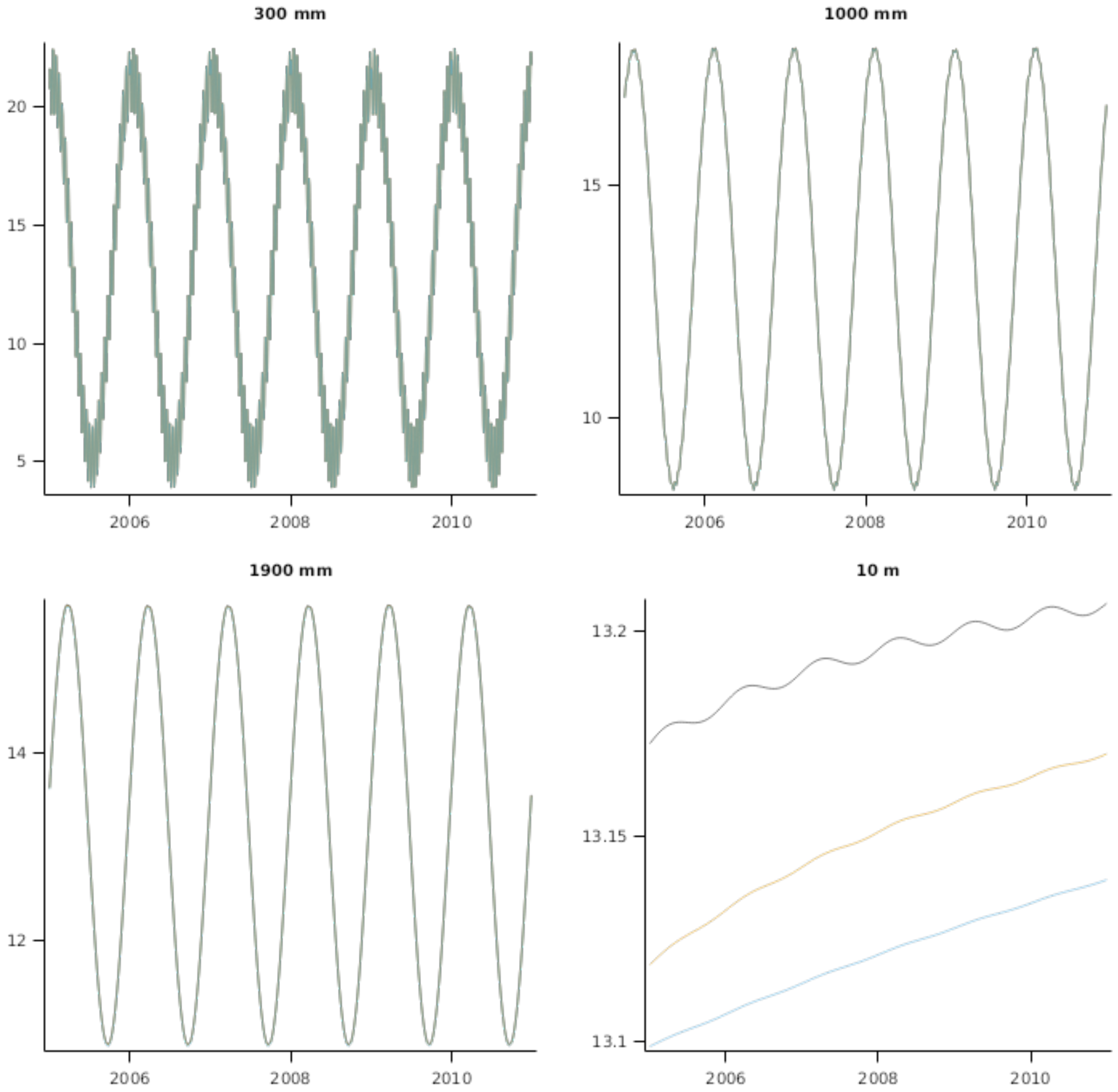




12 SensibilityTests - Depth of Lower Boundary

List of experiments.

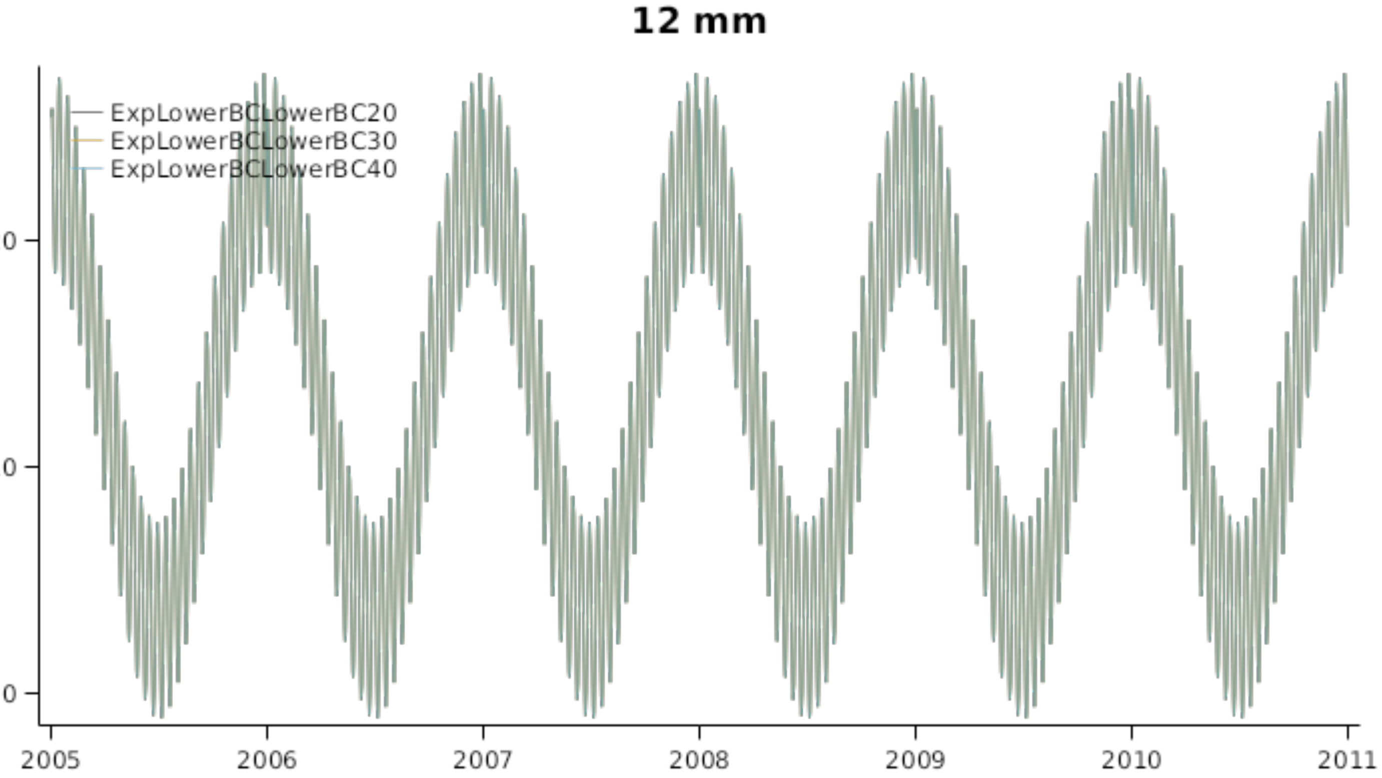
Experiment Name	Design (Number of Treatments)
ExpLowerBC	LowerBC (3)



12.1 ExpLowerBC

The assumed lower boundary condition is that of the location's annual average temperature. That value is asserted as the temperature of the deepest layer in the soil temperature simulation (see the implementation description for more information – this is substantially deeper than the soil profile usually used in APSIM). By default that depth of constant temperature is set to 20 m but users can override that value.

Here a test was created to ensure that the lower boundary depth was sufficiently deep. A successful test is achieved when deepening the lower boundary has no substantive effect on the simulated temperatures. The plots below demonstrate this.


12 mm

13 Comparison of Temperature Models

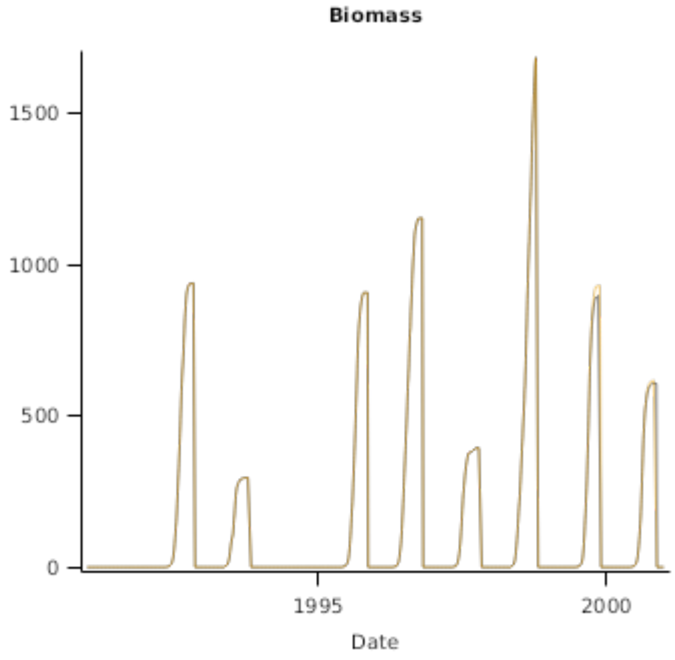
The series of plots below compare the old method for simulating soil temperature (sometimes labelled as CERES but actually from EPIC) against the new numerical simulation. The simulations cover biomass, harvested material and soil temperature at 100 and 1250 mm for wheat grown in Dalby (Australia), pasture in Lincoln (New Zealand) and a maize-soybean rotation in Iowa (USA).

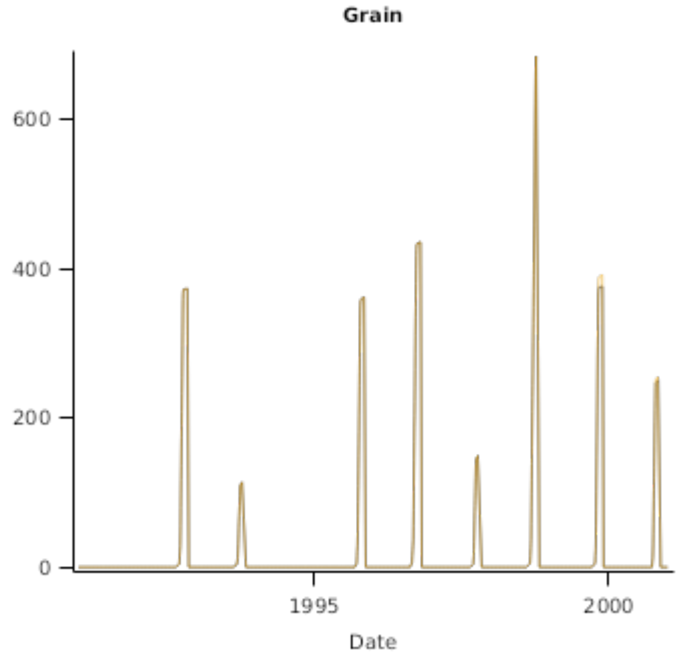
The outputs show relatively minor effects on crop/pasture growth and somewhat more realistic simulations of soil temperature at depth which may be important for simulating freezing in soils.

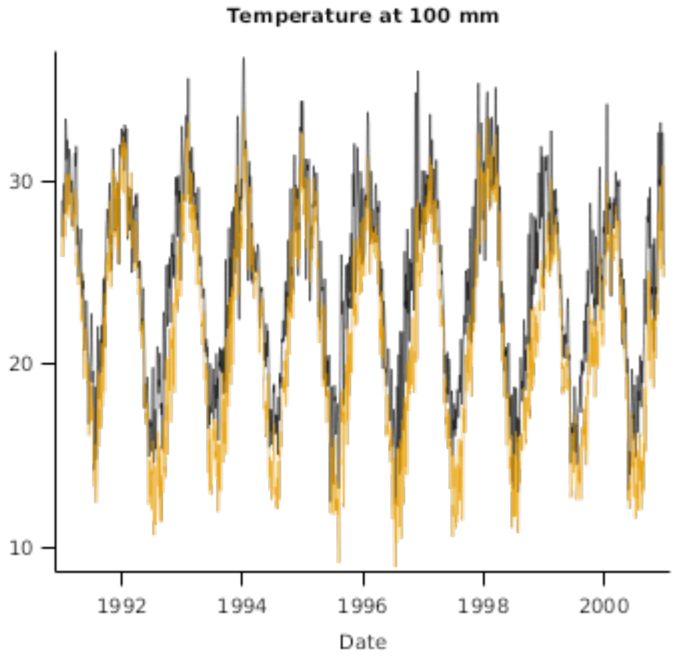
13.1 Wheat in Australia

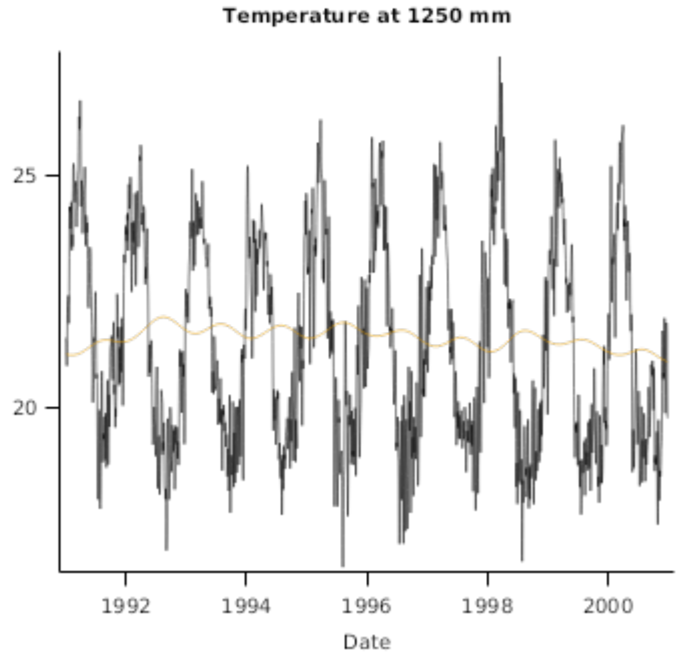
WheatAustraliaEPIC

WheatAustraliaNew





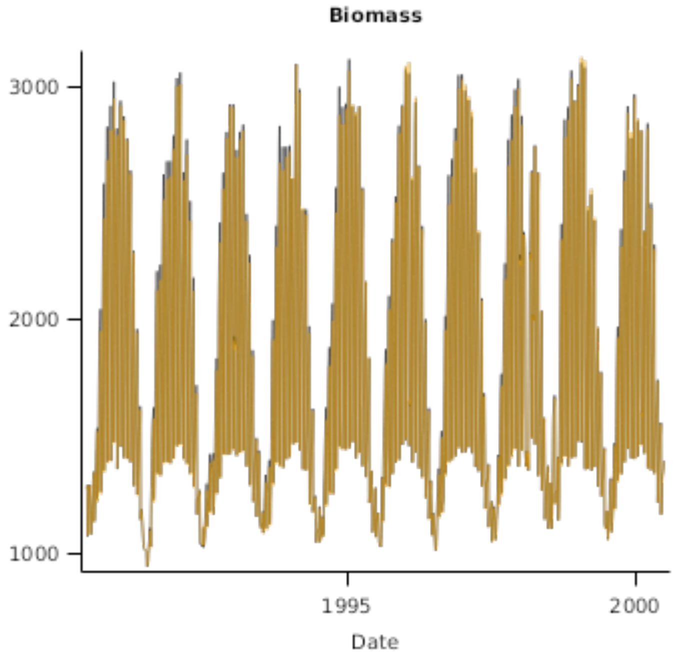


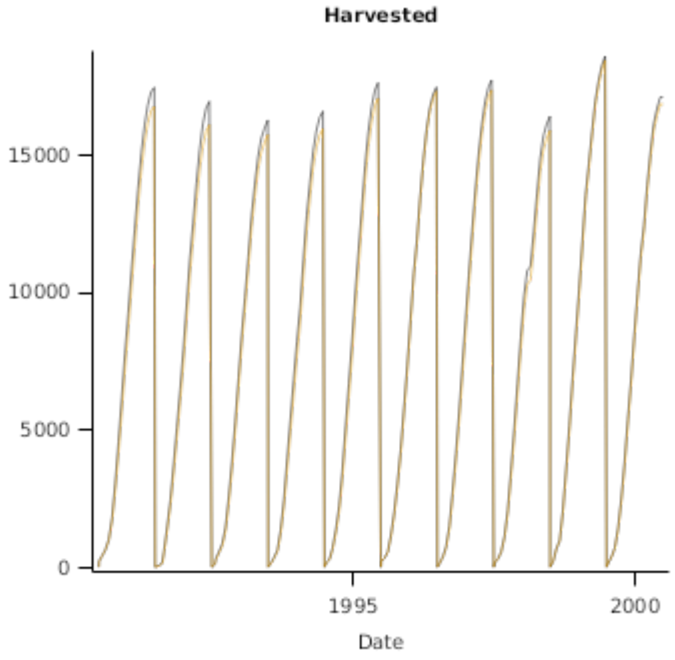


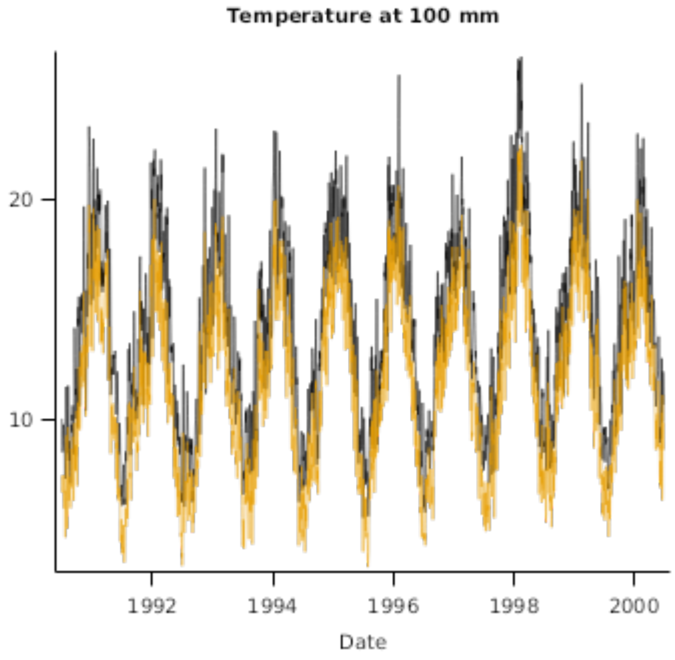
13.2 Pasture in New Zealand

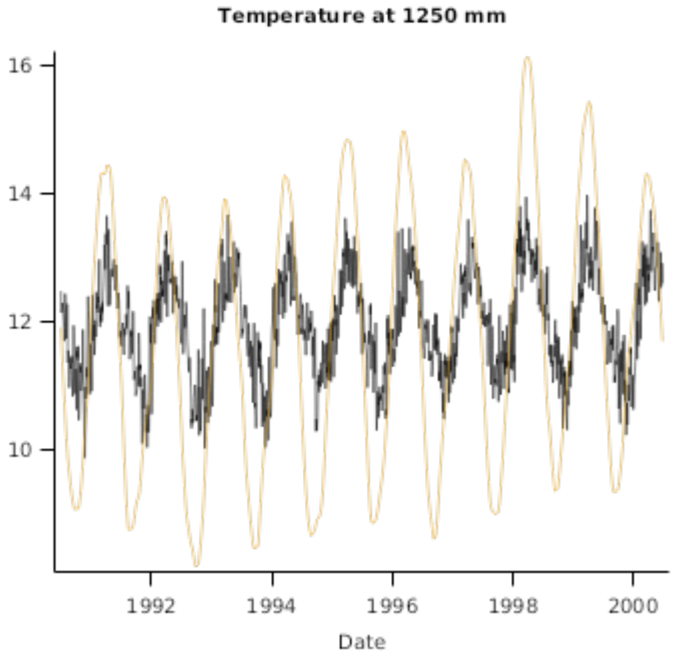
PastureNewZealandEPIC

PastureNewZealandNew


Biomass


Harvested

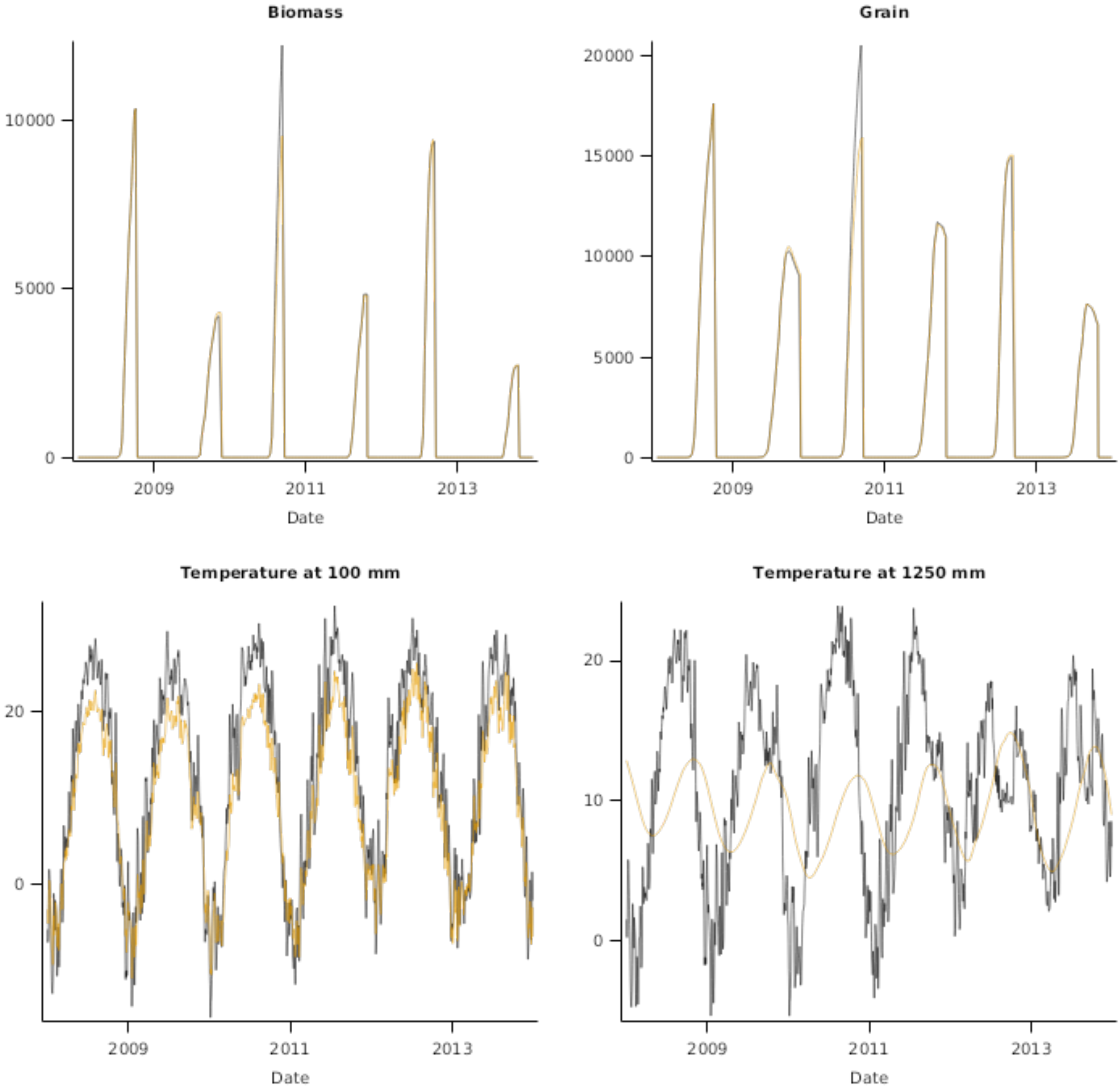

Temperature at 100 mm


Temperature at 1250 mm

13.3 MaizeSoybean in Iowa

MaizeSoyIAEPIC

MaizeSoyIANew


Biomass
10000
5000
0
2009
2011
2013
Date
Grain
20000
15000
10000
5000
0
2009
2011
2013
Date
Temperature at 100 mm
20
0
2009
2011
2013
Date
Temperature at 1250 mm
20
10
0
2009
2011
2013
Date